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Enhancing the Performance of Building Integrated Photovoltaics

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Enhancing the performance of building integrated photovoltaics

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Abstract

Recent research in Building Integrated Photovoltaics (BIPV) is reviewed with the emphases on a range of key systems whose improvement would be likely to lead to improved solar energy conversion efficiency and/or economic viability. These include invertors, concentrators and thermal management systems. Advances in techniques for specific aspects of systems design, installation and operation are also discussed.

Keywords: Photovoltaics; Buildings; Solar concentration; Inverters; Thermal management; Array sizing

1. Introduction

Building Integrated Photovoltaics (BIPV) is a PV application close to being capable of delivering electricity at less than the cost of grid electricity to end users in certain peak demand niche markets (Byrne et al., 1996; Masini and Frankl, 2002). BIPV adoption varies greatly by, and within, country depending upon climate, built environment, electricity industry structure, government polices, local product offerings, market stimulation mechanisms, consumer demand, existing industrial capabilities and the forms of tariff arrangement for grid-connected PV power generation (Green, 2003; Bakos et al., 2003; Watt et al., 1997; Imamura, 1993; Chambouleyron, 1996; Yordi and Gillett, 1997; Hass, 1997; Nieuwenhout et al. 2001). BIPV modularity results in short installation times, and the lack of moving parts reduces the need for maintenance (Yewdall et al., 2002). As Japan and some countries in Europe have low specific land use per capita (for the Netherlands, Japan, German and Switzerland, respectively, this is 2680, 3060, 4450, 6000 m^2 per capita compared with 37,040 m^2 per capita for the USA (Nordmann, 1997)) locating PV on buildings is preferable to specifically devoting land (Strong, 1996a). Grid-connected BIPV – the simplest such low-voltage residential system comprises a PV array and inverter – feed electricity directly to an electricity network operating in parallel with a conventional electric source and do not usually require/use batteries. The performance of a grid-connected system depends on PV efficiencies, local climate, the orientation and inclination of the PV array, load characteristics and the inverter performance (Kurokawa et al., 1997a,b; Simmons et al., 2000; Miguel et al., 2002).

The very extensive current research on photovoltaic cells has been reviewed extensively elsewhere (see, for example; Green, 2003, 2007; Van Kerchauer and Beaucamie, 2005; Kazmerski, 2006).

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Nomenclature

I	insolation ($W\,m^{-2}$)	T	temperature of photovoltaic cell (K)
R	thermal resistance of photovoltaic cell ($KW^{-1}\,m^2$)	η	solar energy electrical conversion efficiency

2. Inverters

An inverter's efficiency in converting PV generated DC power into AC power determines the PV generated DC power required to supply a given AC load which in turn for specified PV array efficiency sets the PV array size. The performance of an inverter depends on its point of work, threshold of operation, grid connection system, inverter output waveform, harmonic distortion and frequency, PV efficiency, maximum power point tracker (MPPT) and transformer. The main functions of an inverter are waveshaping, regulation of output voltage and operation near peak power point (Kjar et al., 2005).

The three major types of inverter are sine wave, modified sine wave, and square wave inverter. The major advantage of a sine wave inverter is that most equipment available commercially is designed for sine wave operation. A modified sine wave inverter (which has a waveform more like a square wave, but with an extra step) will also operate with most equipment. Static inverters use power semiconductor switches which operate at the cut-off and saturation mode and therefore the output of the waveform is a square wave. A square wave inverter will only generally operate simple devices with universal motors but is much cheaper than the sine wave inverter. Using a power filter, the output square waveform can be converted to a sine waveform. An inverter equipped with a MPPT algorithm extracts maximum power from the PV by varying the input voltage to maintain maximum power point (MPP) voltage on the current–voltage curve as PV output varies with insolation and module temperature (Hussein et al., 1995; Hsiao and Chen, 2002; Takashima et al., 2000; Swiegers and Enslin, 1998; Kuo et al., 2001). The efficiency of an inverter depends on the fraction of its rated power at which it operates. A PV system operates at high-efficiency either when it has a sole inverter operating with a load large enough to maintain peak efficiency or is an interconnection of multiple string inverters, module-integrated inverters or master-slave configurations (Woyte et al., 2000). A sole inverter is supplied from several series-connected PV modules switched in parallel on a DC bus; it can be low-cost and provide high-efficiency but entails a complex DC installation. In a module-integrated inverter each PV module has its own individual inverter. Both string and module inverters are more expensive than a central inverter, however, they obviate the need for expensive DC wiring (Woyte et al., 2000). A master-slave configuration entails multiple inverters connected together; at low insolation, the whole string is connected to just a single inverter operating the inverter at its peak input power level, when insolation increases the PV array is divided progressively into smaller units, until every string inverter operates independently at or near its peak rated capacity. Master-slave inverters can give greater BIPV output (Marańda et al., 1998).

AC module-integrated inverters are located generally at the back of each module converting that module's DC output to AC power. The advantages of AC module-integrated inverters are: (i) low resistance losses in cables and connections; (ii) absence of a diode eliminates associated losses; (iii) excess energy can be supplied readily to the utility; (iv) safer than high-voltage DC PV systems; (v) flexibility, ease and low-cost of module installation; (vi) as each module is equipped with a maximum power point tracker, low mismatch losses at system level ensue; (vii) conduction losses and cable costs are low because of the high AC voltage and therefore low current; (viii) lower capital cost due to mass production economies; and (ix) the small size of one AC module lowers barriers to market entry (de Graaf and Weiden, 1994; Wills et al., 1996; de Haan et al., 1994; Yatsuki et al., 2001; Wills et al., 1997). The disadvantages of AC modules are: (i) increased heating of the inverter located at the back of the module; (ii) increased zero load dissipation compared to a conventional PV system; and (iii) for large PV systems, a central inverter system would be cheaper (de Graaf and Weiden, 1994; Wills et al., 1997).

Inverters are either line or self-commutated. Self-commutated inverters operate independently being activated solely by the input power source; an internal frequency generator provides the correct output frequency. Self-commutated inverters can be connected easily to the grid or any other power source which is tied to the inverter output and for a large PV system three-phase devices are used. Though line-commutated inverters have a lower cost, the AC electricity power quality and power factor are both poor. A PV inverter is either a 'voltage source' or a 'current source' inverter. In a current source inverter the DC source acts as a current source to the inverter (Longrigg, 1982) and needs fault-clearing devices. In the voltage source inverter, the inverter acts as an AC voltage source at its AC terminals (Longrigg, 1982). A PV array operates in the constant-voltage region of the I-V characteristics with this type of inverter for stable operation.

Inverter efficiency reaches its maximum usually above 90% efficiency for an input power level usually between 30% and 50% of its rated capacity. However, low efficiency ensues generally at input power levels below 10% of capacity (Rasmussen and Branz, 1981). When a BIPV module is shaded, the PV output current decreases significantly causing not only the particular module output power to drop but the series-connected PV output power also drops which in turn affects inverter performance (Hashimoto et al., 2000). Inverters have been developed specially for BIPV applications with improved maximum power point tracking, reliability and low insolution performance (Kleinkauf et al., 1992; Hashimoto et al., 2000; Shinohara et al., 1992; Noh et al., 2002; Kremer and Diwes, 1998; Stocker et al., 1992; Cendagorta et al., 1998).

Inverter throughput or stand-by losses occur due to (i) operation under low input power resulting in threshold energy loss; (ii) operation under high input power resulting in DC/AC conversion loss due to the protective cut-off being activated (iii) increase in inverter temperatures, (iv) coupling of a number of inverters; (v) use of inverters with low operating efficiency; and (vi) operation at part-load conditions (Baltus et al., 1997; Reinders et al., 1999; Blaesser et al., 1994).

The optimisation of a grid-connected BIPV system depends on the relative capacities of the installed PV array and inverter (Kil and van der Weiden, 1994; Nofuentes and Almonacid, 1998; Marańda et al., 1998; Rasmussen and Branz; 1981; Keller and Affolter, 1995; Coppye et al., 1995; Schalkwijk et al., 1997; Mondol et al., 2006a). Optimum grid-connected BIPV system performance in central Europe can be achieved for an inverter rating of 0.6–0.7 of the array peak BIPV power (Rie and Sprau, 1992; Keller and Affolter, 1992). More generally the optimum ratio of PV array and inverter size for a grid-connected PV system depends on inverter characteristics, available insolation, PV orientation and the PV to inverter cost ratio. Inverter oversizing reduces annual efficiency substantially (Omer et al., 2002, 2003; Mondol et al., 2006a). There are, however, often significant performance differences in superficially similar inverters available commercially (Haeberlin et al. 1997; Veltman et al. 1992). Under the German 1000-roof project it was found that the optimum PV inverter sizing ratio depended on the inverter characteristics and meteorological conditions and varied from 0.8 to 0.9 for low to high-efficiency inverter units when the PV surface was inclined at 45° (Decker et al., 1992). However, PV system performance is less affected when the sizing ratio ranged between 0.7 and 1.3 and 0.7 and 1.1 for a high and low efficiency inverter PV system, respectively (Decker et al., 1992); the effective sizing ratio for a horizontal surface was found to be within 0.7–1.1 for a high-efficiency inverter system and 0.6–0.9 for a low efficiency inverter system. In an investigation of the effect of sizing ratio and PV/inverter cost ratio on the performance of a PV system for various European locations, (Mondol et al., 2007a,b) it was found that for a PV/inverter cost ratio of 6 and for a low efficiency inverter system, the optimum sizing ratio varied between 1.2 and 1.4 for high to low-insolation sites whereas the corresponding variation was from 1.1 to 1.3 for a high-efficiency inverter system.

3. Building integrated PV products and systems

When BIPV displaces conventional building materials, savings in the purchase and installation of conventional materials lower the net cost of the BIPV. BIPV walls, roofs, and awnings provide fully integrated electricity generation while also serving as part of the weather protective building envelope (Archer and Hill, 2001). BIPV can serve as a shading device for a window, a semi-transparent glass façade, a building exterior cladding panel, a skylight, parapet unit or roofing system (Hagemann, 1996; Benemann et al., 1994; Maurus et al., 2004). BIPV system output depends on (Kaye et al., 1997; Sidrach-de-Cardona and López, 1999; Imamura et al., 1992).

- the availability of and access to solar radiation as determined by climate, inclination, latitude, orientation and the urban setting (Norton, 1992; Waide and Norton, 2003; Yun and Steemers, 2009) of available building surfaces,
- PV efficiency and its degradation with time (Simmons and Infield, 1996),
- efficiency of balance of system components (Miguel et al., 2002),
- coupling to the electrical network, electrical wiring resistance and voltage drop in diodes (see Section 4.4),
- partial overshading (see Section 4.6),
- accumulation of dirt, dust or snow on modules (see Section 4.5).

The optimum design of a BIPV system although based on a building's electrical load profile, PV output and balance-of-system characteristics, must be cogniscent of building design constraints, building location, offset costs, climate, and future load growth (Watt et al., 1998a). System economic viability depends on local electrical loads and utility prices (Mondol et al., 2006a). Approximately 25–30% (Sick and Erge, 1996) of energy consumed in buildings in industrialised countries is as electricity. Photovoltaics can be integrated on virtually every conceivable structure from bus shelters to high rise buildings. BIPV modules fabricated directly onto building materials, can, in high-volume production lead to lower substrate, distribution and installation costs (Jäger-Waldau, 2006). There would be some additional cost associated with the BIPV wiring, but this would be minimal in new construction. The peak power cost for large-scale, BIPV systems could drop to less than $1/Wp, which should lead to PV electricity costs comparable to large centralised power plants, i.e., less than 10 cents per kWh (Lin and Carlson, 2000). Moreover, since some of the PV power would be used in the building, the demands on the power grid are reduced and the reliability of supplied power to the building is improved. With the advent of low-cost storage, a network of BIPV systems could become a reliable, distributed power source, which would be immune to widespread disruptions (Lin and Carlson, 2000). Another potential significant advantage is that the heat collected by PV modules can also be used for space heating or hot water-heating (see Section 8.3). From architectural, technical and financial perspectives (Rüther, 1998; Archer and Hill, 2001; Sick and Erge, 1996; Posbic and Rever, 1998; Yoo et al., 1998; Oliver and Jackson, 1999), BIPV

- when grid-connected, avoids the costs of batteries, associated BOS and possible system oversizing;
- reduction of investment costs by displacing façade/roof/shading elements;
- can be aesthetically appealing;
- electricity is generated at the point of use, reducing the impacts, costs and losses associated with transmission and distribution (Paatero and Lund, 2006);
- is suitable for unshaded roofs and facades in densely populated areas;
- no additional land area required, since building surfaces used;
- can be designed to generate electricity at a building's peak usage times particularly for commercial buildings, thus reducing the building's peak grid electricity demand;
- may satisfy all, or a significant part, of the electricity consumption of the building;
- can act as shading devices (Sala et al., 1996; Von Bussue et al., 1996; Miller et al., 2005);
- can form semi-transparent elements of fenestration (Maurus et al., 2004);
- PV/T can provide part of the water or space heating loads of the building (see Section 8.3) or more specific uses by, for example acting as the evaporator of a solar-assisted heat pump system (Ji et al., 2008);
- BIPV can form part of a grid-failsafe antennae system for cellular communications (Roo Ons et al., 2007, 2008).

BIPV can be of the form of (i) roofing materials, (ii) wall and fenestration materials (Bendel et al., 1995), and (iii) flexible photovoltaic modules (Shinjo, 1994; Uehara, 1997) and can be integrated to the roof of new buildings or where major roof replacement is undertaken. Methods of integration include exchangeable PV shingles, prefabricated PV roof panels, and insulated PV roof panels (Shinjo, 1994). Fully-integrated BIPV roofing systems must perform the function of a standard roof and provide water tightness, drainage, and insulation. Most retrofitted roof-mounted systems are though not however fully integrated into the roof structure (Watt et al., 1999; Yamawaki et al., 2001). Roofs offer an attractive location for BIPV because of:

- unshaded solar access,
- the cost is offset partially by the displacement of roofing materials by BIPV modules (Nitta et al., 1994) (Chowdhury et al., 1997),
- flat roofs generally enable more optimal solar cell placement and orientation, and
- when a pitched roof is near optimally inclined, the need for and cost of a support frame is eliminated.

A methodology combined data for land use, population building densities with statistically representative maps of urban areas provided by a vectorial geographic information system to determine estimate the roof area available for PV in Spain and it geographic distribution (Izquierdo et al., 2008). Though the method used a limited set of 16 representative building typologies it was found to be scalable and provided the error associated with the estimate.

Many roof-integrated (as apposed to roof-mounted) BIPV are module-based roof tiles (Bahaj et al., 1998), slates (used on flat roofs), shingles or standing seam (for tilted roofs) units. The design of a PV tile or shingle conforms usually to regional or local roofing methods and building codes, so the market for one particular BIPV roofing system may not be applicable to a wide range of countries and many proprietary roof-integrated BIPV systems are available. The "Solbec" system for integrating photovoltaic modules on flat roofs (Bonvin et al., 1997) is made of fibre elements and available in three sizes with multiple possible configurations, easy maintenance and a quick interlocking mounting process. The "SOFREL" modular flat roof PV integration system (Muller et al., 1996) uses standard prefabricated concrete slabs with concrete plinths whose base includes ballast to maintain the structure in place. The wiring of the module is placed underneath the concrete base (Schalkwijk et al., 1995). In the "PowerGuard" PV roofing assembly system, a-Si PV modules act as insulation to the roof protecting the roofing membrane (Dinwoodie and Shugar, 1994) thereby eliminating need for a PV support structure. A frameless exchangeable PV shingle using monocrystalline or polycrystalline cells as shown in Fig. 1 (Okuda et al., 1994; Yagiura et al., 1997) consists of solar cells encapsulated between tempered glass and a metal back plate with an integrated mounting bracket. A roof-integrated PV module made of untempered glass is shown in Fig. 2 (Nitta et al., 1994). The "SUNSLATE", PV-roof and façade system is made with an integrated contact bar, diode on a standard roof or façade slate (Posnansky et al., 1997), the solar cell is encapsulated between solar glass and a coated aluminium sheet and embedded into ethylene vinyl acetate. Another PV roof tile using monocrystalline silicon solar cells has been developed with the upper and underside of the tile made of acrylic and polyvinylchloride, respectively. To enable integration with conventional roofing tiles, it has easy replacement and installation and simple wiring connections (Bahaj et al., 1998). A particular type of a-Si shingle developed to replace conventional roofing shingles (Izu et al., 1994) was several times longer than conventional roofing shingles. In another integral a-Si alloy-based photovoltaic roofing element, the top outer cover of the module is made of fluoropolymer film and laminated to the cell surface using EVA material (Nath et al., 1994, 1998);. the module being of similar shape to a conventional batten and sheet metal roofing element, was used as a standing seam-roofing element using an integral locking system to join panels. The "solar tile" PV roof tile has been developed for integration into clay roof tiles (Meier and Hasler, 1992). Many BIPV roofing

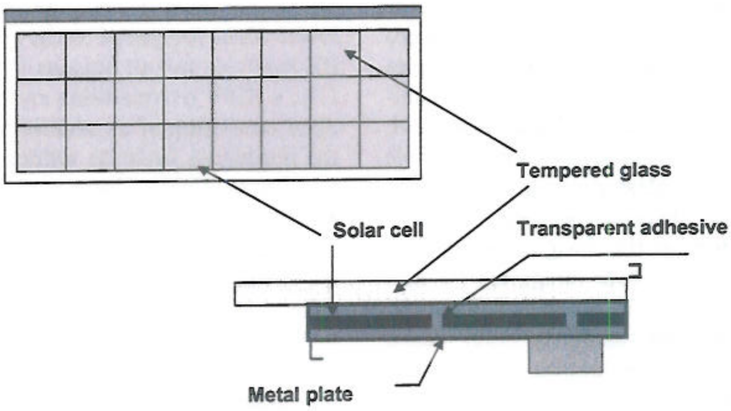

Fig. 1. Structure of exchangeable PV shingle (Yagiura et al., 1997).

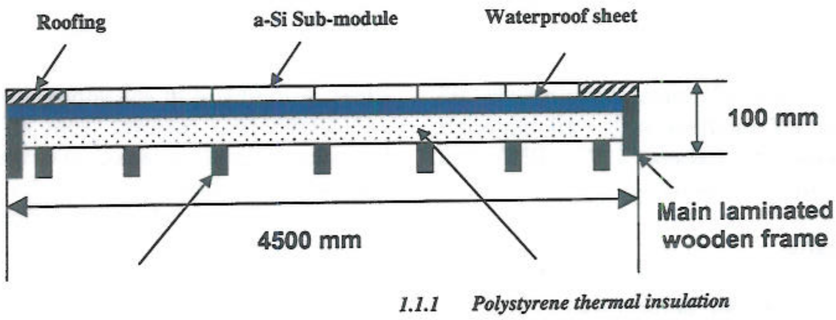

Fig. 2. Sectional view of a roof-integrated PV module (Nitta et al., 1994).

modules have been developed whose size and shape are the same as conventional tiles and interconnected by waterproof leads (Matsuoka et al., 1990; Strong, 1996b; Ishikawa et al., 1994a; Horigichi et al., 1996; Yoshida et al., 1996; Murata et al., 2003). An example is shown in Fig. 3.

PV roof tiles with static concentrators provide cost savings by reducing the PV area using low-cost concentrating elements (Bowden et al., 1993; Wenham et al., 1995). A roof tile has been developed using low-cost lenses (Bowden et al., 1993, 1994). The front surface of the high-efficiency bi-facial solar cell module is covered with glass, the rear

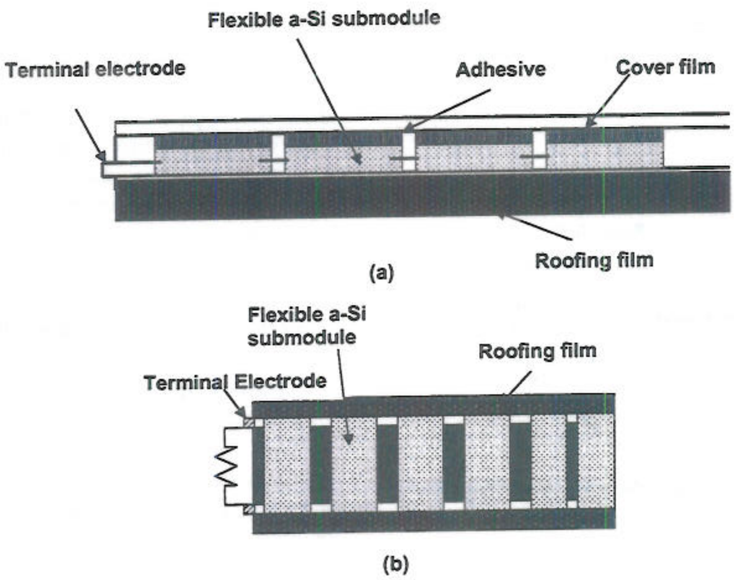

Fig. 3. Structure of solar roofing (a) sectional view; (b) front view (Ishikawa et al., 1994a).

surface is reflective and grooved. The static concentrator was constructed from acrylic. The construction of the module is shown in Fig. 4. Both atria and skylight technologies are suitable for PV integration, with transparent PV laminates replacing the glazing units directly. Large frameless, lightweight, roof-integrated PV modules are available made of transparent, toughened glass with toughened float glass on the front and back surfaces (Wambach, 1998). Several studies have reported on the design, installation, and the performance of such glass roof-integrated PV systems (Reijenga and Böttger, 1997; Humm and Toggweiler, 1993; Sala et al., 1995; Mosko and Niephaus, 1995). James et al. (2009) undertook a critical evaluation of electricity generated, shading provided and comfort enhanced by a atria with semi-transparent PV roof glazing elements in the UK climate. It was found that taking all those factors into account could render the total system viable both economically and in regard to averted carbon dioxide emissions.

PV glass curtain-walls and PV metal curtain-walls are used for integration of PV modules with wall materials (Shinjo, 1994; Toyokawa and Uehara, 1997). BIPV can be integrated into the building facade as:

- rainscreen overcladding,
- structural glazing mullion/transom curtain-wall systems,
- pressure plate mullion/transom curtain-wall systems,
- panel curtain-wall systems, and
- profile metal cladding.

The outer leaf of rainscreen cladding acts as a rain barrier and the inner leaf acts as an air barrier (Scott et al., 1992). Crick et al. (1995) proposed design guidelines of PV rainscreen overcladding, as installed in the, UK (Hill et al. 1994). Curtain-wall façades consist of a metal frame with transparent and opaque panels. A PV module integrated with a metal curtain-wall composed of glass, EVA, polycrystaline silicon solar cells and aluminium base plate has been developed for use in Japan (Yoshino et al., 1997). The module temperature was approximately 10 °C lower when compared to the conventional superstrate-type PV modules for all seasons (Yoshino et al., 1997). In the UK, a BIPV overcladding and curtain-wall has been developed consisting of an aluminium heat sink on the back of the module in order to reduce the PV temperature (Bahaj and Foote, 1994). Lloret et al. (1995) reported a ventilated element consisting of a PV laminate for use in facades. BIPV modules have been developed as conventional glazing elements on facades and roofs (Benemann, 1994; Laukamp et al., 1994).

When PV systems are integrated onto the building façade using a pressure plate system, the glazing unit is mechanically held from the front by a plate with an extended cover; minimal, mullion cap depth is essential to avoid PV shading. Alternatively, the flush application of a structural silicone seal between curtain-wall framed PV glazing units eliminates shading but can give rise to delamination due to moisture ingress at less durable PV panel edges. A double-wall envelope minimises sealing problems and allows heat removal from PV modules. PV glazing forms an external, unsealed layer with the inner layer forming a weathertight enclosure. In designing for building integration of PV it is obviously crucial that the structure is capable of bearing the wind-loaded weight of PV modules. Overheating of PV elements may result due to weathertight seals; for example a sealed façade in Austria produced 4% less energy annually when compared to a cooler rear ventilated system (Wilk, 1994). Design for natural ventilation behind the BIPV elements can enable a temperature reduction of up to 20 K to be achieved (see Section 8). This both increases the electrical output and reduces building heat gain (Brinkworth et al., 1997). Aesthetic appearance is important particularly for prestige commercial curtain-wall façades and has led to the manufacture of coloured PV cells. The need to accommodate wiring in façades, which are often designed to appear frameless can also impact adversely upon façade appearance (Watt et al., 1999). Glazed PV modules (c-Si and a-Si) and modules which are deposited onto a metal or other substrate (a-Si) require different approaches to fabric integration (Crick et al., 1998). Façades are shaded more frequently than roofs; non-homogeneous shading of a PV façade will impact upon the electrical configuration, including the number of series and parallel strings, redundant interconnections and inverter sizing (Groehn and Brathels, 1994).

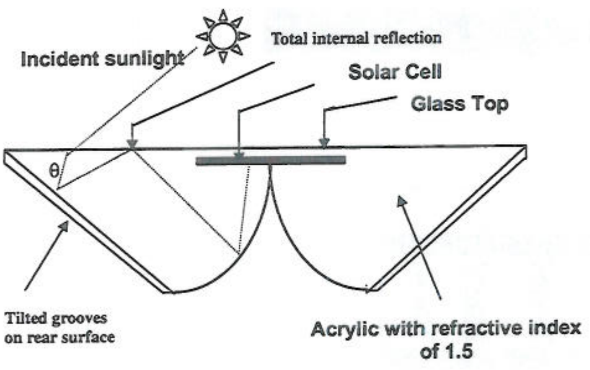

Fig. 4. Construction of PV roof tile with static concentrator (Bowden et al., 1994).

4. Performance of grid-connected BIPV systems

4.1. System performance ratio

The system availability of BIPV system during sun hours is defined as the number of hours of load requirements in a period divided by number of hours for which insolation was sufficiently intense for the system to generate power (Jahn et al., 1994, 1998). The performance ratio (PR) expresses the performance of a PV system in comparison to a lossless system of the same design and rating at the same location (i.e., the system efficiency under realistic reporting conditions (RRC) divided by the module efficiency under standard test conditions (STC) (Simmons and Infield, 1996)) and indicates how close a PV system approaches ideal performance during real operation (Blaesser, 1997). The PR is independent of location and is influenced by:

- insolation (as the efficiency of PV array depends on irradiance);
- the combined efficiency of the system components;
- relative sizing ratio of inverter and PV array, i.e., ratio of inverter rated power to the PV rated power; (see Section 2);
- the extent to which the system output is being used (Mondol et al., 2006b); and
- system layout (Blaesser et al., 1994; Decker and Jahn, 1997; Mondol et al., 2006a; Baltus et al., 1997).

The PR of systems with identical PV modules, inverters and BOS components can differ by up to 30%, mainly due to shading losses (Decker and Jahn, 1997). Average BIPV PR should reach, and preferably exceed, 70% (Kurokawa et al., 1997a; Haas et al., 1999; DeGheselle, 1997; Miguel et al., 2002; Pietruszko and Gradzki, 2003). A BIPV system PR of less than 70% is indicative of a combination of some of the following factors:

- Long-term partial shading (Steinhardt et al., 1998); Sugiura et al., 2003; Schroeder and Kreider, 1998).
- Inverter operation under or near its threshold energy (Sidrach-de-Cardona and López, 1999; Mondol et al., 2007a,b; Ubertini and Desideri, 2003; Bahaj et al., 2001).
- Inverter shutdown during high insolation or power failure (Simmons and Infield, 1996; Sugiura et al., 2003).
- Unstable inverter control and failure of magnetic circuit breakers (Sugiura et al., 2003).
- Coupling problems between the inverter and the grid (Sidrach-de-Cardona and López, 1999).
- High PV temperatures (Pearsall et al., 1997, see also Section 8 of this paper).
- Winter snow cover (Kiefer et al., 1995), and
- Inefficient MPPT (Bahaj et al., 2001, see also Section 4.4. of this paper).

4.2. Sources of losses

PV system losses comprise: (i) avoidable losses which include the difference between actual nominal power, manufacturer's rated power and mismatch losses and (ii) unavoidable losses which include transmittance, low irradiance and temperature losses (Caamaño and Lorenzo, 1998). Table 1 shows losses associated with a PV system (Townsend et al., 1994; Sugiura et al., 2003; Schaub et al., 1994; Steinhardt et al., 1998; Kiefer et al., 1995; Baltus et al., 1997; Decker et al., 1992; Imamura, 1994; Simmons and Infield, 1996; Mukadam et al., 1995; Peterson et al., 1999; Suzuki et al., 2002; Anis and Nour, 1995; Román et al., 2006; Fanney et al., 2001).

4.3. Spectral and optical losses

PV device output varies according to their specific spectral selectivity as the solar spectrum alters due to changes in air mass and relative humidity (Hirata and Tani, 1994) an −1% to −2% annual spectral loss is associated with modules that have a broad spectral response (Nann and Emery, 1992; Bücher, 1997) and a +4% to −15% for a narrow spectral response (Bücher, 1997). Better spectral matching has been shown to give rise to higher PV efficiency in summer (Rüther and Dacoregio, 2000). Larger average air mass at

Table 1
A summary of percentage losses in PV systems due to operational parameters.

Source of loss									Reference
Reflection (%)	Temperature (%)	Inverter (%)	Low irradiance (%)	Shading (%)	Soiling (%)	Ohmic (%)	Mismatch (%)	MPPT (%)	
–	3.0	7.8	–	7.1	–	–	3.8	–	Sugiura et al. (2003)
–	8.0–17.0	10.0–16.0	–	–	3.5–5.0	1.0–1.5	0.15–0.17	2.0–5.0	Mukadam et al. (1995)
–	–	15.0	–	–	–	2.5	2.0	–	Decker et al. (1992)
–	–	–	–	–		–	–	15.0	Caamaño and Lorenzo (1998)
–	–	–	–	35.0	10.0	–	–	–	Becker et al. (1997)
3.1	7.6	4.0	0.9	0.3	–	1.2	5.7	–	Iliceto and Vigotti (1998)
–	3.3	5.3	–	3.5	–	0.24	–	–	Steinhardt et al. (1998)
–	3.8	17.5	4.6	11	–	1.2	5.7	–	Baltus et al. (1997)
–	2.8	13.2	–	1.7	–	2.1	9.8	4.5	Schaub et al. (1994)
–	2.2	6.9	–	4.1	–	–	5.1	–	Kurokawa (1998)
–	4.0	8.0	–	7.0	–	–	6	–	Kato et al. (2002)
–	3.3	5.3	–	3.5	–	–	–	–	Jahn et al. (1998)
–	–	–	–	–	4.0	1.2	0.2	0.6	Durand et al. (1990)
–	–	10.0	–	–	3.0	–	5.0	–	Lloret et al. (1998)
2	4	15	7		1.5	1.0	1.0	2	Mondol et al. (2007)

low sun angles shift the spectrum towards red causing a decrease in efficiency (Pratt and Burdik, 1988).

Reflection loss from the module surface, (also referred to as angular loss) depends on module orientation and tilt angle, solar position and geographical location of the site (Reinders et al., 1999; Martin and Ruiz, 2001) with the reflection loss being higher for vertical surfaces close to the equator (Bücher, 1997). Anti-reflection coatings are included in many modules. Fig. 5 illustrates the dependence of angular loss on location and tilt angle and Fig. 6 shows the variation of annual angular loss as a function of tilt angle for different European locations. The measured yearly reflection losses of crystalline modules have ranged within 6.7–10.8% with reflection loss increasing from 10% to 13% as the PV orientation changed from the optimal to vertical orientation (Lanzerstorfer et al. 1995) and declining at least 2% when PV inclination changed from 48° to 90° (Preu et al., 1995).

Accrual of dirt and other particles on a PV module surface reduces insolation transmission (Goossens and Kerschaever, 1999; Reinders et al., 1999; Gonzalez, 1986). Annual soiling losses vary from 2% to 8% but in dry summers soiling loss could be over 20% (Maag, 1977; Townsend and Whitaker, 1997). Soiling loss depends on the module front surface material, the site microclimate and local dust sources, the frequency of cleaning by rain or manually (Hoffman and Maag; 1980), and increases with the inclination of the PV surface (Nakamura et al., 2001).

4.4. Electrical losses

The efficiency of a PV module decreases when it operates at irradiance level lower than STC resulting in a drop in module efficiency due to recombination currents, parallel resistance, and other effects (Bucher et al., 1998). The low irradiance loss could be within the range of 1–5% (Iliceto and Vigotti, 1998; Baltus et al., 1997). Typically there is a 1–3% resistance (or ohmic) loss (Mukadam et al., 1995; Decker et al., 1992) due to cable resistance, contact resistance in terminals, fuses and connectors or disconnectors. There are two primary losses associated with any array circuitry: the loss due to the resistivity of the array wiring series resistance; and that due to drops in array voltage in diodes (Gonzalez, 1986).

Mismatch loss is caused by variation between I-V characteristics of coupled PV modules due to manufacturing defects and inhomogeneous and/or partial shading caused by surrounding objects. Mismatch loss is due to either current mismatch or voltage mismatch (Gonzalez, 1986). Current mismatch occurs when low current modules are present in a series string or when a portion of the array is shaded; if the current and voltage of the modules are not matched, modules providing low output determine the overall array output. Voltage mismatch arises when cells are shorted (Gonzalez, 1986). Cells connected in series or parallel operate at the same current or voltage resulting in significant energy loss when the operation of cells is limited by the cell power with the lowest peak output (Bucciarelli, 1979). Mismatch loss can be determined by either measuring the I–V characteristics of each string and comparing them with each other or measuring the real array efficiency in the field and then making corrections for the module temperature and cable losses (Baltus et al., 1997). PV modules generate maximum power when the array voltage is equal to the voltage at the MPP (Baltus et al., 1997). Maximum power point tracking (MPPT) loss occurs when the power produced by a PV array deviates from the expected value. This loss can be two types: static MPPT loss which is determined by the efficiency of the MPPT under stable irradiance conditions (Reinders et al., 1999),

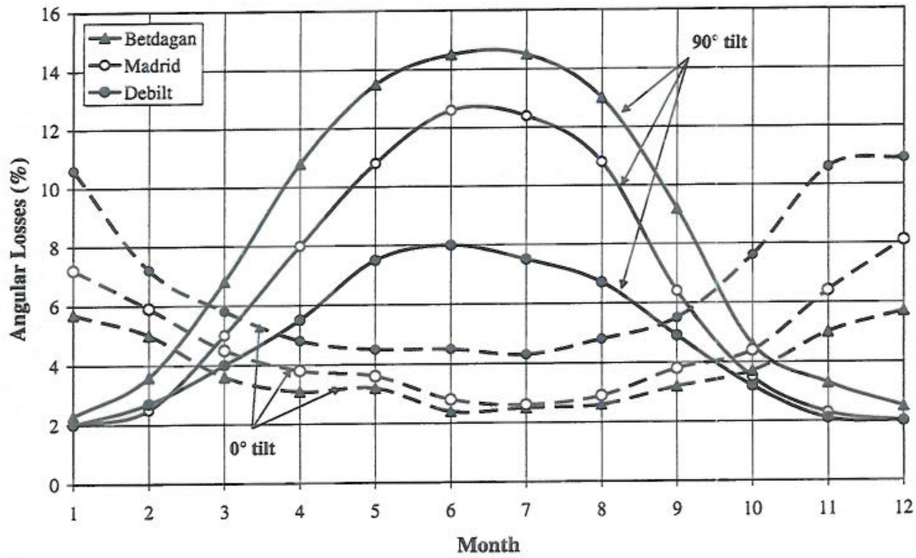

Fig. 5. Monthly angular losses of a standard m-Si module as a function of tilt angle for three locations (Martin and Ruiz 2001).

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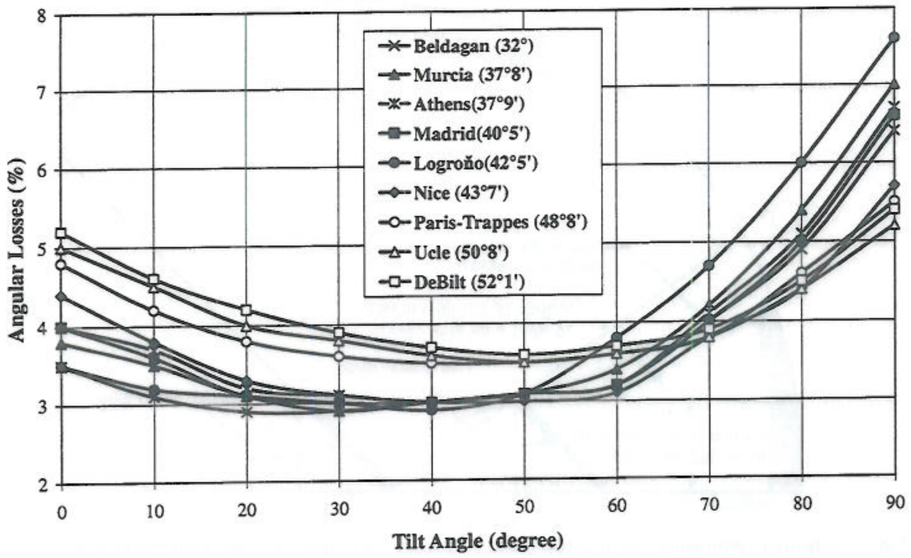

Fig. 6. Annual angular losses as functions of tilt angle for different sites (Martin and Ruiz 2001).

and dynamic MPPT loss caused by a slow MPPT searching algorithm; fast fluctuating insolation causing rapidly varying array power that may not be detected correctly by a slow voltage domain tracker (Reinders et al., 1999). Generally the lowest MPP losses occur when modules are sorted based on MPP current and highest when sorted by voltage (Wilshaw et al., 1997). The incremental conductive method of MPPT has been shown (Román et al., 2006) to give the best performance.

Array capture losses are – often indeterminate – combinations of thermal capture losses caused by the operating temperature of the module and miscellaneous losses caused by wiring, string diodes, low irradiance, partial shading, dirt accumulation, snow covering, inhomogeneous irradiance, cell mismatching, maximum power point tracking, inefficient system components or system failures (Miguel et al., 2002). PV cells also lose power output over time, aging of cells can reduce power to as much as 80% of original power over 20 years. The initial loss of PV efficiency is due to the Steabler–Wronski effect, (Simmons and Infield, 1996; Van Dyk et al., 2002; Rüther and Dacoregio, 2000) it is suggested that maximum power point tracking devices should be based on the degraded module performance. The DC PR of an a-Si PV system typically falls from 80% to 65% due to initial system degradation (Ossenbrink et al. 1994; Dunlop et al. 1997). Applying separate MPPT to each module (rather than to the array as a whole) allows it to operate at maximum power irrespective of the possible shading or differing orientations of other modules in the array (Román et al., 2008).

4.5. Tilt angle, orientation and seasonal losses

Using a validated simulation model, the maximum annual system PR of a roof-mounted BIPV system at a latitude of 54°N in the UK was found to be for a south facing surface inclined at 20°. For horizontal and vertical south facing surfaces the system PR was estimated to be 1.6% and 18.1% lower, respectively, than the maximum value (Mondol et al., 2007a). For a location at latitude 35.7°N maximum annual energy was obtained for the surface with tilt angle 29° (Soleimani et al., 2001). For both these locations, these optimal inclinations show the strong contribution diffuse insolation can make to the total solar energy incident annually on a BIPV array.

For seasonally-tracking arrays, annual PV output can be 94% to 96% of the maximum annual PV output when optimum tilt angle is selected only once a year and 99% of the maximum annual PV output if the optimum angle is adjusted twice a year (Balouktsis et al., 1987). Different methods are available to obtain optimum tilt of a PV system based on the latitude, local climates, insolation conditions and energy demand (Tsalides and Thanailakis, 1985; Kern and Harris, 1975; Bari, 2000; Mondol et al., 2007a) and location — specific measurements have been reported of the seasonal dependence of PV system performance (Rüther, 1998; Marion and Atmaram, 1990; Oladiran, 1995; Akhmad et al., 1994; Sopitpan et al., 2001; Pearsall et al., 1997; Molenbroek et al., 1998; Itoh et al., 2001; Hiraoka et al., 2003).

4.6. Shading losses

Shading can, as shown in Fig. 9 result in an output energy loss of 25% (Gross et al., 1997). Shading loss arises due to the difference of insolation on shaded and unshaded parts of a PV array (Schroeder and Kreider, 1998; Alonso et al., 1997; Lloret et al., 1998; Omer et al., 2003; Budin and Budin, 1982; Blewett et al., 1997). Shading loss may be due to the diffuse component of insolation being different on different modules (Gonzalez, 1986) as shown in Fig. 7, or

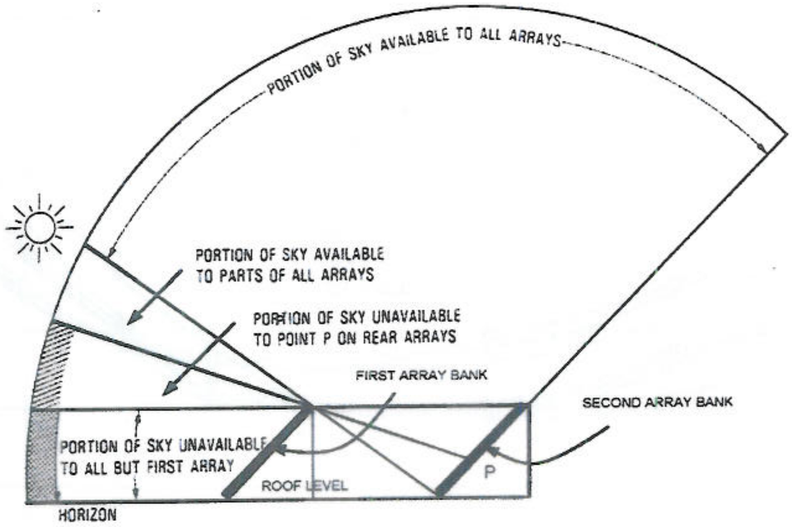

Fig. 7. Schematic representation of array shadowing from the diffuse radiation component (Gonzalez, 1986).

obstruction by other arrays or nearby objects (Reinders et al., 1999; Alonso et al., 1997). Shading affects PV performance by (Alonso et al., 1997): (i) hot-spot formation due to non-uniform illumination causing heating of the module and performance detoriation; (ii) reduced inverter performance due to instability in inverter MPP tracking and/or (iii) poor output waveform quality due to the decrease in the MPP voltage. Shading loss can be reduced by using modules with cell-integrated bypass diodes, employing small-scale inverters and using MPP trackers (Quaschning and Hanitsch, 1998; Bruendlinger et al., 2006). As shown in Fig. 8 relative shading loss increases with raised shading angle. Ilíceto et al. (1997) reported that the partial shadowing during early and later parts of a day in winter months caused a 5% energy loss that reduced the yearly performance by only 0.3%. Whereas Omer et al. (2002, 2003) found a 27% reduction of annual PV output for two BIPV systems in the UK. Lloret et al. (1998) observed 3% power losses due to shading effects and soiling losses.

5. Economic optimisation and viability

5.1. Sizing parameters

BIPV sizing depends on the following:

- Insolation: PV output varies directly with the amount of insolation available at the site. Other climatic factors which influence PV output are: temperature, precipitation, wind speed and land topology. The scattering of

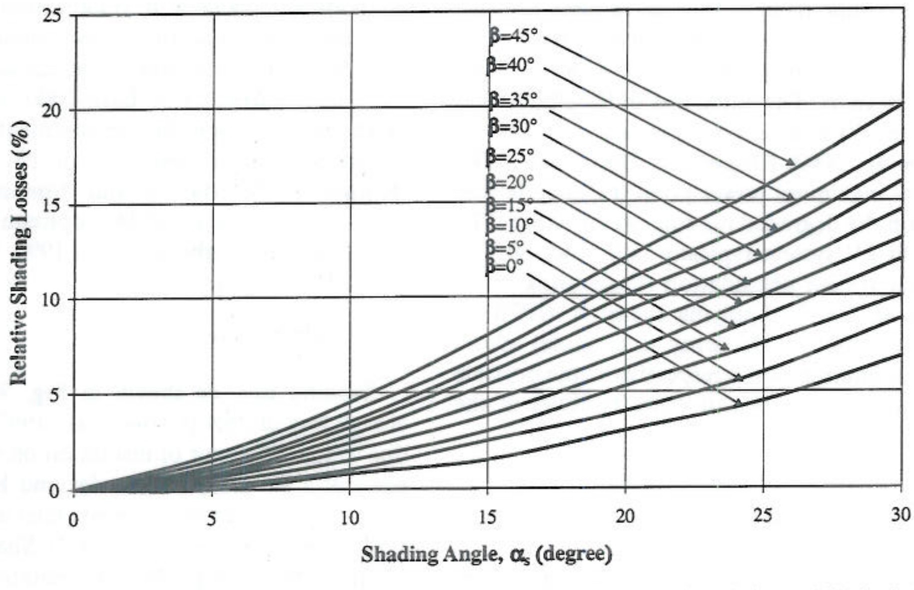

Fig. 8. Relative shading loss as a function of shading angle and module tilt angle (Quaschning and Hanitsch, 1998).

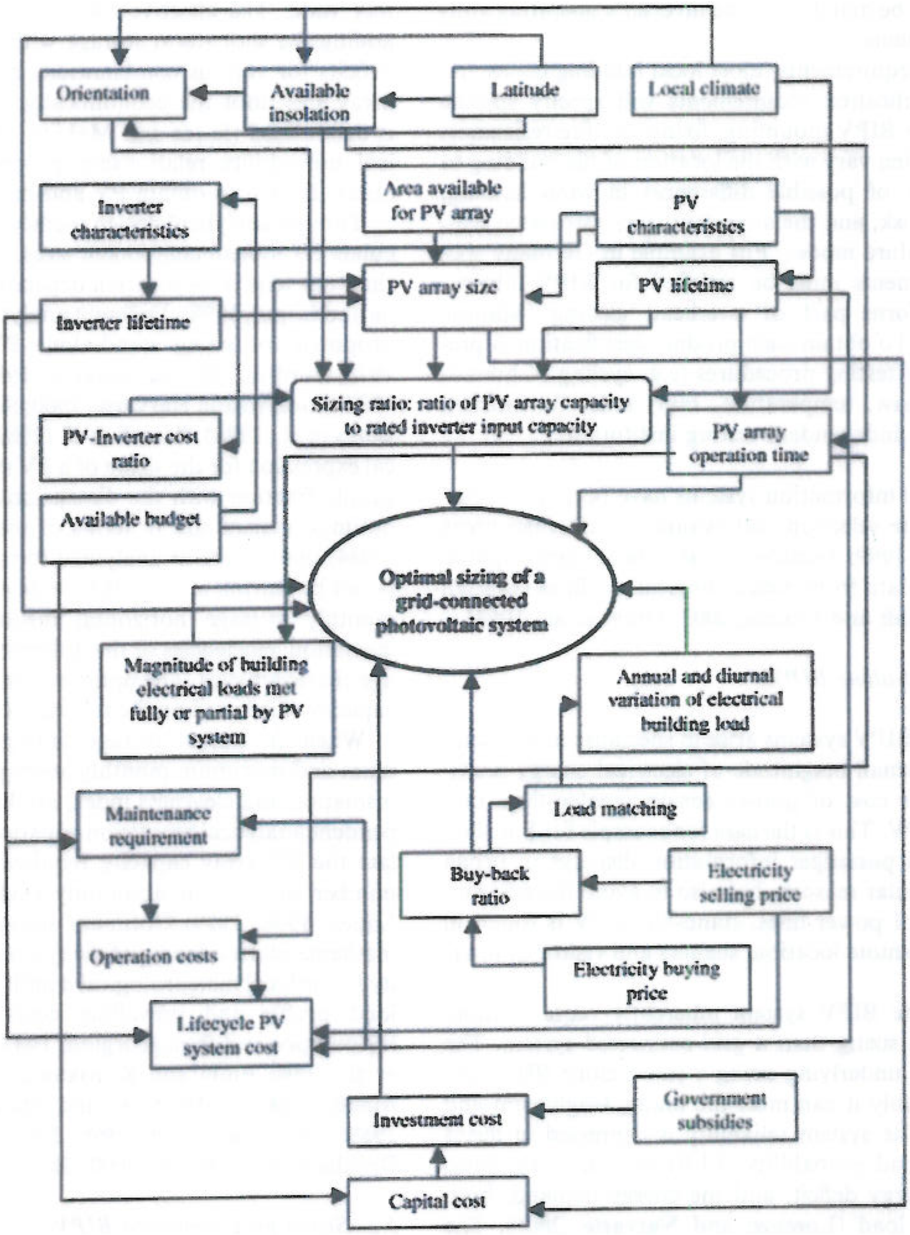

Fig. 9. Interactions of influences on PV system sizing (Mondol et al., 2006a).

albedo from snow-covered ground, inclination of the surface and the characteristics of topology of the terrain in front of the PV plants may increase the performance of a PV system (Brack et al., 1992; Sugiura et al., 2003).

- Nearby roof structures and surrounding objects can cause shading which will reduce PV performance.
- Area: PV installations require larger surface areas to meet larger loads. For a BIPV system, orientation and inclination also affect PV output with optimum orientation and inclination usually determined to be the surface which receives the highest utilisable (i.e., can be harnessed by a load) insolation (Mondol et al., 2006a).
- Economics: The economic factors which influence the cost of PV generated electricity are PV and BOS cost, and installation costs. In addition any grants, incentives subsidies or special purchase arrangements are important factors (Sick and Erge, 1996).
- Load: A realistic estimation of load profile to be satisfied is the first step in the design of a stand-alone BIPV system design. For a stand-alone PV system, the operating voltage is selected equal to the voltage required by the largest load (Sharma et al., 1995). In grid-connected BIPV applications the economically optimal diurnal load to be met by the PV will not correspond to the total load particularly at night and (in high latitude locations) in winter. For a grid-connected BIPV system overproduction on an annual basis must be avoided (though such gross oversizing is unlikely) and the DC system

voltage must be matched to the inverter's operating voltage requirements.

- Regulatory requirements: most local building codes and product certification requirements will specify specific standards for BIPV mounting, fixing and fire resistance. These will often vary with the location of the building to take account of possible differences in wind loading, earthquake risk, and the attendant risks associated with particular failure modes. For example in Germany specific requirements must be satisfied for BIPV fabrications that form part of overhead glazing (Maurus et al., 2004). To obtain such product certification, a prescribed set of testing procedures (e.g. cycling of humidity, freeze/thaw, temperature, rain) must be satisfied usually in an independent testing institution.

Geographical information systems have been used effectively for PV site selection and evaluation in urban areas (Muselli et al., 1999; Gadsden et al., 2003), using spatial solar radiation data from meteorological satellites (Muselli et al., 1998; Maafi and Lounis, 2002; Otani et al., 1994).

5.2. Sizing stand-alone BIPV

Stand-alone BIPV systems arise in specialist small buildings where the small magnitude of electrical energy provision renders the cost of grid-extension greater than that of installing BIPV. This is the case for example for bus shelter lighting and passenger information displays in urban settings. For similar reasons, but also to avoid the environmental impact of power lines, stand-alone PV is found in many park, or remote location, shelters and visitor or interpretive centres.

A stand-alone BIPV system inherently requires more accurate system sizing than a grid-connected system. The primary criteria underlying sizing a stand-alone BIPV system is how reliably it can meet the load (Benghanem and Maafi, 2000). The system reliability is expressed in terms of the loss of load probability (LLP) defined as the ratio between the energy deficit, and the energy demand, both referred to the load (Lorenzo and Narvarte, 2000). The main sizing parameters of a stand-alone BIPV system are PV array and storage capacity and the LLP (Narvarte and Lorenzo, 1996). PV array capacity is the ratio of mean PV energy production to the mean energy load demand. The storage capacity is the ratio of mean energy taken out from the accumulator (battery) to the mean load energy demand. Methods have been proposed for sizing stand-alone PV systems which can be divided into: (i) intuitive methods, (ii) numerical methods, and (iii) analytical methods (Sidrach-de-Cardona and López, 1998). Intuitive methods provide an initial rough estimate of the likely system dimensions (Sidrach-de-Cardona and López, 1998; Lorenzo and Narvarte, 2000).

When using numerical methods, PV and battery size are calculated by means of system simulation using either an hourly or daily energy balance of the system and the battery state. The effective battery capacity is estimated by adding the short-term storage with the year-round energy deficits for various combinations of PV surface slope and array size until the economically optimum configuration is determined (Soras and Makios, 1988). A similar analytical utilizability relationship proposed by Bartoli et al. (1984) is used to obtain PV and battery size.

Though analytical design methods are easy to use to calculate PV system component sizes, their main drawback is that they tend to be location dependent (Sidrach-de-Cardona and López, 1998). Different analytical methods have been proposed for sizing stand-alone PV system (Bucciarelli, 1979; Gordon, 1987; Bartoli et al., 1984; Egido and Lorenzo, 1992; Lorenzo and Narvarte, 2000; Soras and Makios, 1988; Barra et al., 1984). Bartoli et al. (1984) proposed an analytical expression for the sizing of a PV system which relates PV supply fraction with the dimensions of its components to optimise system size in terms of overall cost. Barra et al. (1984) used a similar analytical form of the equations proposed by Bartoli et al. (1984) to develop a model that used monthly average horizontal insolation, extra-terrestrial insolation, efficiencies of the different components and storage characteristics. The optimisation of the PV and storage capacity was based on the minimum system cost.

When the annual average daily global insolation, minimum and maximum monthly average daily global in-plane insolation and clearness index, are known, a location independent analytical regression equation can be used to calculate the PV array capacity required to satisfy a specified number of days of autonomy (Sidrach-de-Cardona and López, 1998, 1999) Optimum sizing techniques based on mathematical modelling of the system components, sensitivity to the local meteorological conditions, system reliability, load profile and prevailing costs have been reported (Groumpos and Papageorgiou, 1987; Negro, 1995; Notton et al., 1996; Endo and Kurokawa, 1994; Benghanem and Maafi, 2000; El-Hefnwai and Hanafi, 1998; Chapman, 1989; Lasnier and Juen, 1990; Kaye, 1994; Shrestra, 1998; Benghanem and Maafi, 2000; Sharma et al., 1995).

5.3. Sizing grid-connected BIPV

Grid-connected BIPV systems may be designed at different times to (i) meet a fraction of total electrical load of the building, (ii) have all their output delivered to a grid and/or (iii) deliver excess energy generated into the grid. The optimum sizing of a grid-connected BIPV system is influenced by many factors as illustrated in Fig. 9 (Mondol et al., 2006a; Sick and Erge, 1996, Oshiro et al., 1997; Yukawa and Kurokawa, 1994; Hernández et al., 1998; Nofuentes and Almonacid, 1999; Peippo and Lund, 1994a,b). The many simulation tools developed for designing and simulating BIPV systems can be categorised as:

- Pre-feasibility tools: determine the viability of a BIPV system for a particular application in terms of energy production and the life-cycle cost of the system.

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Table 2
Features of PV System Design Softwares (Bates et al., 1998).

PV f-Chart	For design and analysis of PV systems. Estimates monthly average performance of a PV system by calculating total in-plane insolation from horizontal insolation. Array efficiency calculated using cell temperature. Predicts long-term performance from monthly weather data
SOLCEL-II	Uses hourly values of the horizontal and direct normal radiation, ambient temperature, wind speed and in-plane insolation to predict PV output. Maximum power tracking; floating battery; voltage regulator; and temperature degraded efficiency are employed to simulate the hourly performance of the system.
PVWATTS	An internet accessible tool that simulates electrical energy output of a grid-connected PV system for US locations
PVSYST	For design and analysis of stand-alone and grid-connected PV systems. Simulates of a PV system using an inbuilt geographical and meteorological database and 3D CAD facility for visualisation and computation of nearby shading; considers losses including temperature losses, mismatch losses, wiring losses and reflection losses with provision for analysis of measured data capable of modelling of grid-connected system with different inverter(s) configurations and different load profiles
PVSOL	For design and optimisation of PV systems. Tool has a large PV and inverter manufacturers database, it accepts user defined component specifications; it is applicable to any PV surface inclinations and orientations; it considers shading effects, it considers partial load performance of inverter unit; allows sizing capability of PV and inverter capacity; it considers different load profiles and utility tariff rates and performs economic analysis by considering the system replacement and the investment residual value
PVSIM	Models PV cells, modules and arrays using I–V characteristics of cells which includes short circuit current, series resistance, shunt resistance, ideal diode saturation current, non-ideal diode saturation current, diode quality factor for the non-ideal diode, and cell temperature. The programme also includes the effect of blocking diode and bypass diodes in array circuits
PVFORM	For stand-alone and grid-connected applications. Global horizontal insolation, ambient temperature and wind speed are inputs to this program. The programme also considers a system with an MPP tracker and simulates a power conditioning unit using partial load efficiency
TRNSYS	Transient System Simulation is a sequential-modular simulation program that provides dynamic simulation of a PV system. The component models which are either empirical or analytical, describe the component performance with algebraic differential equations. System simulation is performed by interconnecting individual components
ENERGY-10 PV	Applicable for a BIPV grid-connected PV system which allows users to study hourly interactions between the building load and the PV array. This tool works with the design software ENERGY-10 and uses TRNSYS simulation programs for simulation of PV systems
PHANTASM	Developed for BIPV applications, is an extension of the TRNSYS program and therefore uses TRNSYS subroutines which require PV characteristic parameters, the transmittance of the glazing, absorptance of the PV cells, the electron band gap and NOCT parameters for the simulation

- Sizing tools: determine the optimal size of different components of a BIPV system based on the life-cycle cost and the purpose of the system used (Simones et al., 1984).
- Simulation tools: perform detailed analysis of the behaviour of a system when given the nature and size of the system. These tools are used to investigate the impact of the load profile, verify the system sizing, investigate system performance under typical conditions and provide information regarding the financial and environmental characteristics of the system.
- Open-architecture research tools: these are flexible in nature, offer modification of existing components or addition of new components into the main programme.

Some simulation tools have been developed specifically for PV system modelling as shown in Table 2, such as PVNet (Bishop, 1988); PVNETSIM (Schilla et al., 1997), PVNode (Stellbogen, 1992), PVSS (Goldstein and Case, 1978), RETScreen (Bakos et al., 2003), simPhoSys (Schmitt, 2002), and Renew (Woolf, 2003). General transient solar energy simulation modules such as TRNSYS (Klein et al., 2000) have also been used successfully for BIPV simulation (Mondol et al., 2005, 2006a,b, 2007a). Different simulation tools can:

- Be applicable to a wide range of grid-connected, stand-alone or hybrid PV systems (Endo and Kurokawa, 1994) Model individual BIPV components (Krenzinger and Wagner, 1992; Gow and Manning, 1999; Sukamongkol et al., 2002), particularly inverters (Jantsch et al., 1992).
- Provide detailed algorithms to take account of particular aspects of component behaviour; for example low-insolation PV module performance (Smiley and Stamenic, 2002).
- Include different sky radiation models (Louche et al., 1994). The choice of such models can have a significant effect on accuracy of the calculation of insolation on inclined BIPV planes (Mondol et al., 2008). Furthermore the accuracy of different anisotropic (Perez et al., 1990) and isotropic sky models varies seasonally in many locations, though twelve values of monthly mean insolation are adequate for the calculation of annual electrical output (Perpiñan et al., 2008).
- Use measured insolation data (Moser and Inamura, 1994; Park et al., 2001a,b).
- Consider urban site parameters (Snow et al., 1999) including orientation and shading (Caamaño and Lorenzo, 1996; Almonacid, 1995).
- Account for electricity tariffs and building energy loads (Travers et al., 1998; Mondol et al., 2006a).
- Encompass economic factors such as interest rates and relative fixed acquisition costs (Weidele et al., 1996) or environmental, regulatory and policy factors.

5.4. Viability criteria

For a BIPV system, the economic viability is determined by the generated electricity cost (i.e., profitability or the cash flow implications of the original BIPV investment decision) in competition with that of other (usually grid) electricity (Lazou and Anastassios, 2000; Oliver and Jackson, 2000, 2001). Conventional energy sources usually have small initial costs and relatively large operating costs whereas BIPV systems require higher initial investment costs but smaller operating costs (Goswami et al., 1999). Parameters such as discount rate, escalation rate, inflation rate and system lifetime influence significantly the economic performance of a system. The simple payback period of a BIPV system is calculated from the total investment cost divided by the first year's revenues from grid electrical energy displaced (Bakos and Tsagas, 2002). A more complex realistic payback period is the time at which the initial cost and the annual expenses equals the energy saving cost with compounded interest (Böer, 1978). A PV project is viable economically when the invested capital plus a minimum acceptable rate of return is recovered within a service life shorter than the technical service life (Lasnier and Ang, 1990). Life-cycle cost analysis (LCC) considers all the costs associated with an energy delivery system over its life time and all other future costs or cash benefits, and discounts them to their present value (Duffie and Beckman, 1991). As anticipated future costs are brought back to present costs by calculating how much would have to be invested at a market discount rate to have the funds available when they will be needed (Duffie and Beckman, 1991) it enables comparison of the delivered costs of technologies with different cost structures (Bhuiyan et al., 2000). The life-cycle cost includes both initial capital cost and the year-to-year operating costs of the BIPV system and can be expressed as the sum of capital equipment cost, acquisition costs, operating costs, interest charged on borrowed capital, maintenance, insurance, and miscellaneous charges, taxes, recurring costs associated with the system and salvage value (Goswami et al., 1999). Keoleian and Lewis (1997) presented a life-cycle inventory model to compare the economic performance of BIPV with conventional grid-connected systems. There are differences in the embodied energy of BIPV systems due to different transmission and distribution losses and replacement of conventional building materials: the energy embodied per kWh of electricity generation for centralised PV, BIPV cladding systems and glass cladding systems have been estimated as 11.4MJ, 4.15MJ, and 2.6MJ, respectively (Oliver and Jackson, 2001).

When the payback period of a grid-connected BIPV system is calculated considering variable tariff rates, inclusion of flat-rate net metering and battery storage (where storage supplied energy to the load at the peak load time) the shortest BIPV pay back period ensues for PV energy stored at the off-peak time and sold to the grid at peak times (Khouzam, 1997). For favourable discount rates, low operation and maintenance expenses and high insolation sites, Chabot (1998) estimated a PV electricity cost of 0.122 $\$\mathrm{kW\,h}^{-1}$, this was close to prevailing domestic electricity tariffs. Often, however, the breakeven cost of a PV system remains dependent on the electrical load (Nishikawa et al. 1992), this can vary significantly with occupancy and building characteristics both in non-domestic and domestic buildings (Yohanis et al., 2008). From a utilities' viewpoint the cost of BIPV electricity depends on its capacity to meet peak demand. Saving peak load demand removes the need for capital, and recurrent investment in auxiliary energy systems such as expensive gas turbines or hydro storage. For a BIPV system, this presents an opportunity to maximise economic performance by saving peak building-load demand (Koner et al., 2000). Effective demand saving depends on load profiles, available insolation and peak demand tariff rates all being appropriate. In warm-climates, peak load demands occur generally on hot sunny days when to air-conditioning electricity usage coincides with the most productive period of BIPV electricity generation. For a system with no storage, this occurs when BIPV output matches with the utility or the building's peak load. A BIPV array connected via power conditioning equipment to the building's distribution panel is referred to as 'non-dispatchable' because it has no battery storage and so energy flow from the system is not managed to meet peak demand. Peak saving occurs when system output coincides with the building peak load demand. The peak saving of a BIPV system is influenced primarily by two factors: (i) significant fluctuations in capacity factor and (ii) an uncertain match between solar irradiance and daily building peak load. When the peak BIPV output and peak load do not match closely, the use of storage could improve peak saving benefits (Byrne et al., 1996). Control units have been developed to optimise load matching by managing energy flow from the BIPV system to the load through battery storage (Palomino et al., 1997). These control units supply energy to the building load during the peak load times and direct BIPV energy into storage at off-peak periods. Frei et al. (1997) found that the average percentage of maximum output with respect to daily load reached close to daily peak load for a system with 1.25 h of storage showing the advantage of using a storage system for reduction of peak load demand.

A study into PV supply and load demand considering different weekdays and weekend load patterns (Rahman et al., 1990), showed that the PV supply and load demand generally matched well, however, in winter peak PV generation hours fell short of the peak load demand of the building due to short sunshine duration. Conversely if the grid voltage increase due to PV power flow is close to the upper voltage bound of the power distribution line's control range, it would be necessary to restrict PV output (Ueda et al., 2006). If the electricity buying and selling prices are the same, then consumers will not benefit by changing their load profile (Haas, 1994). If the selling price is less than the buying price consumers will benefit by shifting their on-peak load demand to the peak PV supply, alternatively if the buying price is greater than the selling price consumers will gain more by selling more electricity to the grid by shifting PV peak supply to the off-peak load demand times with energy storage and flow management (Mondol et al., 2006b).

5.5. Balance-of-systems costs

Module array frames, electrical cables, DC–AC inverters, regulators, switch gear, batteries and safety equipment are referred to as balance of system (BOS) components. BOS costs are typically half of the total system cost (Roberts et al., 2001) and the area-related BOS costs increases as the PV efficiency decreases (Whitaker and Real, 1999). To reduce the total system cost and hence the unit cost of BIPV generated electricity it is vital to reduce both BOS and PV module manufacture costs. Reduced BOS costs can be achieved through simplification of the installation process to minimise labour, standardisation of components to reduce inventory and training complexity and increasing cell efficiency. As an example of the latter, a 20% efficient module requires only half the area, support structures and cabling required for a 10% efficient product. By the end of year 2000 some 200 retail gas station canopies in 9 countries had been fitted with 18 kW_p to 40 kW_p PV installations; in the course of installing the first 100 systems, installation unit cost halved through design and components standardisation building integration and common installation procedures (Roberts et al., 2001).

Material choices and component design can improve significantly BIPV efficiency and longevity. Ethylene vinyl acetate co-polymer is now the common encapsulant material as it suffers no discolouration due to moisture absorption that ensued in early modules that used polyvinyl butyralate. Near-surface protection is typically a multilayer film of Tedlar® and polyester. Polyester has largely replaced aluminium as the moisture barrier layer as aluminium had a tendency to cause short-circuits in cell strings (Roberts et al., 2001). Larger module dimensions have reduced the cost of both non-cell components in the module and installation. Terminal boxes are being replaced with flying leads and weather-proof in-line plugs and sockets to reduced significantly on-site installation costs (Roberts et al., 2001).

6. Optical solar energy concentrators for BIPV

The cost of wide-scale implementation of BIPV as a building façade cladding can be reduced by substitution of some of the expensive photovoltaic materials by lower cost concentrating systems (Zacharopoulos et al., 2000; Eames et al., 2000; Gajbert et al., 2007; Bowden et al., 1993, 1994). Either trapping light within screen-printed solar cells (Green, 1995) or using reflective/refractive devices to increase the luminous power flux onto the solar cell surface (Luque et al., 1995) ensures that solar cells convert the additional power incident without significant loss of efficiency. Static parabolic trough concentrators for different receiver locations have been reported for photovoltaic applications (Kabakov and Levin, 1994). Practical non-imaging concentrators (Winston, 1974, 1975; Welford and Winston, 1979; Winston, 1980; Leutz et al., 1999b, 2000; Winston and Hinterberger, 1995) are designed with one or two pairs of acceptance half-angles that accept diffuse insolation. Concentrated solar fluxes are thus non-uniform with the diffuse fraction contributing to flux distributions at the absorber in non-imaging solar concentrators with low concentrations typically employed in stationary BIPV systems (Gajbert et al., 2007; Rabl, 1985). Non-imaging systems can be made either by using a refracting lens or by using reflective mirrors (Boes and Luque, 1992). Compound parabolic concentrators (CPC), (Welford and Winston, 1978), concentrate the radiation from the aperture to the receiver and can significantly increase the electric power yield for a unit area of PV. Because of its wide angle of acceptance, the CPC can modestly concentrate solar energy without diurnal tracking of the sun (Brogren et al., 2001), and therefore can reduce the PV cell area required decreasing the cost of PV generated electricity.

The concentration ratio determines the increase in relative radiation at the surface of the exit aperture/absorber. The geometrical concentration ratio is defined as the ratio of the area of aperture to the area of the receiver (Duffie and Beckman, 1991). The optical concentration ratio indicates the proportion of incident rays within the collecting angle that emerge from the exit aperture (Winston, 1980; Rabl, 1976a). A CPC can be designed for different absorber shapes giving rise to a range of different reflector designs. For the CPC with a tubular absorber, detailed parametric and experimental analyses of optics and heat transfer have been undertaken (Eames and Norton, 1993a,b, 1995; Eames et al., 1999). Models can predict performance accurately for changes in geometry reflectance, emittance or thermal conductivity, and incident insolation intensity and distribution (Eames et al., 1999). A refractive three-dimensional symmetric CPC has been employed as a concentrator for photovoltaics (Brunotte et al., 1996). Asymmetric compound parabolic concentrator designs have been reported (Rabl 1976a,b; Smith 1976; Mills and Giutronich 1978, 1979; Winston and Welford 1978; Blanco et al., 1986; Mullick et al., 1987; Kienzlen et al., 1988; Norton et al., 1991; Zacharopoulos et al., 2000; Adsten 2002 and Mallick et al., 2002a,b). An ideal extreme asymmetric concentrator (EAC), (Smith, 1976), collects solar energy within the maximum acceptance half-angle at a fixed concentration. However, the long second reflector leads to a large number of reflections being required for rays to reach the receiver, which leads to higher optical losses and lower optical efficiency. In a subsequently developed EAC (Mills and Giutronich, 1979), the mirror was located relatively close to the receiver providing a larger acceptance angle for rays reflected from the mirror, reducing the number of reflections. This allows an increase in aperture area which compensated for losses due to rays passing through the gap between the receiver and mirror (Winston and Welford, 1978). 'Sea shell' asymmetric concentrators (Rabl, 1976b) are shown in Figs. 10 and 11. The system in Fig. 10

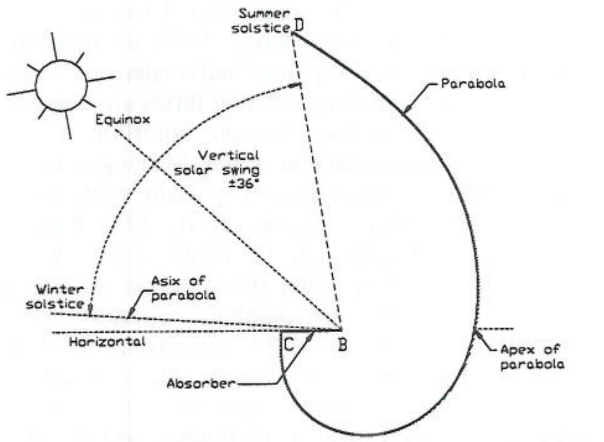

Fig. 10. Stationary 'Sea Shell' collector with variable concentrations, with maximum output in the summer (Rabl, 1976b).

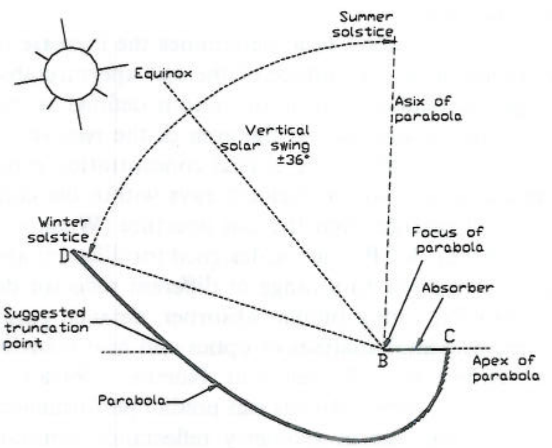

Fig. 11. Stationary 'Sea Shell' collector with variable concentrations, with maximum output in the winter (Rabl, 1976b).

was designed for maximum output in summer and has an acceptance half-angle of 36° providing a collection time of 7 h. The system in Fig. 11 was designed to achieve maximum output in winter. The "Maximum Reflector Collector" (MaReCo) was characterised experimentally for high-latitude bi-facial cell BIPV applications (Adsten, 2002). Different MaReCo configurations were made for stand-alone, roof integrated, east/west, spring/fall and wall integration. A cross-section of a stand-alone MaReCo is shown in Fig. 12 (Adsten, 2002). Fig. 13 illustrates that the cross-section of roof integrated MaReCo designed for Stockholm conditions (Adsten, 2002). The highest optical efficiency reported was 56% for a bi-facial based MaReCo. In contrast, optical efficiency of 91% was predicted for dielectric-filled BIPV covers (Zacharopoulos et al., 2000) and 85% for an air-filled asymmetric CPC BIPV system (Mallick et al., 2002a).

A novel non-imaging asymmetric compound parabolic photovoltaic concentrator (ACPPVC) was designed, constructed and experimentally characterised (Mallick et al., 2004a) for BIPV applications. The use of this ACPPVC

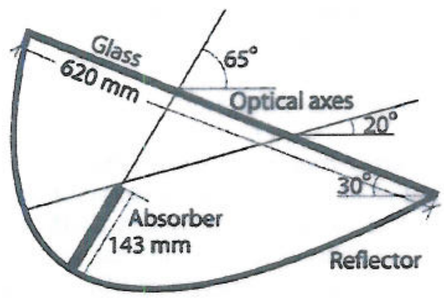

Fig. 12. Section of the stand-alone MaReCo for Stockholm conditions. Aperture tilt 30°. Optical axes 20° and 65° defined from the horizon (Adsten, 2002).

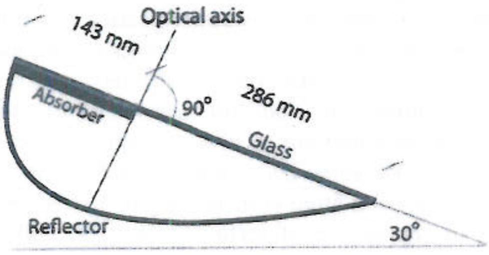

Fig. 13. Section of a roof integrated MaReCo design for a roof angle of 30°. Optical axis perpendicular to the cover glass (Adsten, 2002).

increased the maximum power by 62% (i.e. the power by a factor of 1.62) when compared to the same PV system without concentrating elements (Mallick et al., 2004b) for a designed geometrical concentration ratio of 2. The performance was less than that anticipated due to increased back plate temperatures which were on average 12 °C higher (Mallick et al., 2006) and ohmic losses in interconnections between the solar cells.

Non-imaging Fresnel lens concentrators for medium concentration photovoltaic applications have been designed, manufactured and a comparative cost analysis reported (Leutz et al., 1999a,c). A truncated non-imaging Fresnel lens was analysed using a ray trace analysis (Welford, 1978) for minimal optical aberration. Variable acceptance half-angle pairs have been designed for use with a non-imaging Fresnel lens applicable to BIPV (Leutz et al., 2000). The optical concentration ratio undergoes a sharp decrease once the incidence angle exceeds the design acceptance half-angle. A non-imaging static concentrator lens was developed for the conditions in Sydney, Australia utilising refraction and total internal reflection to give a geometrical concentration ratio of 2.0 and a lens efficiency of 94% (Shaw and Wenham, 2000). The annual averaged optical concentration ratio was 1.88 for direct insolation within ±60° and ±25° in the East–West and North–South directions, respectively. A "flat plate static concentrator" with optical efficiencies of 87.6% and 85.6% was reported for mono-facial and bi-facial cell BIPV applications (Uematsu et al., 2001a). It was reported that 90% of the annual irradiation could be collected by the mono-facial

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system with a concentration ratio of 1.5 and the bi-facial system with a concentration ratio of 2.0 (Uematsu et al., 2001b). Optical efficiencies of 94.4% (Uematsu et al., 2001c) based on a two-dimensional raytrace programme were reported for the FPSC system with a prism array. The front and rear illumination efficiencies were reported to be 15% and 10.5%, respectively (Uematsu et al., 2003). However, Uematsu et al. (2001a–c) did not take into account the effect of increased temperatures on the photovoltaic solar cells conversion efficiency. Static concentrators, as shown in Fig. 4, offer a compromise between high concentration systems that require tracking and non-concentrating flat-plate modules (Bowden et al., 1993). A "slimline" design was reported to achieve a concentration ratio of four (Wenham et al., 1995). Thermal analysis indicated that performance loss through additional heating of the PV was more than offset by the gains achieved through concentration. The efficiency of the module was reported to be 15% greater than that of the flat-plate module (Wenham et al., 1995). Cu(In,Ga)Se_2 solar cells with low concentration compound parabolic and plane reflectors for low concentration photovoltaic applications (Wennerberg et al., 2000; Brogren et al., 2003) showed a maximum electric power increase of 1.9 times with a fill factor decrease from 0.6 to 0.5 when compared to cells without the concentrator (Brogren et al., 2003).

Dielectric non-imaging concentrating covers for PV integrated building façades use total internal reflection within the dielectric material to provide optimal optical efficiency (Shaw and Wenham, 2000; Zacharopoulos, 2001; Korech et al., 2007). A three-dimensional optical analysis has showed that an asymmetric concentrator design is more suitable for building façade BIPV compared to a symmetric concentrator. Both asymmetric and symmetric concentrators had an optical efficiency of 81% for a wide range of solar incidence angles. The asymmetric concentrator maintained optical efficiencies of over 40% even for incidence angles outside its two-dimensional angular acceptance range. The comparative energy collected by a symmetric dielectric concentrator and a flat-plate cover are shown in Fig. 14 (Zacharopoulos et al., 2000).

*P*hotovoltaic Facades of *R*educed Costs *I*ncorporating *D*evices with Optically Concentrating *E*lements (PRIDE) technology incorporating 3 and 9 mm wide single crystal silicon solar cells showed excellent power output compared to a similar non-concentrating system when it was characterized indoors using both a flash and continuous solar simulator. However, durability and instability of the dielectric material occurred under long term outdoor characterisation when the concentrator was made using casting technology. For large-scale manufacturing, durability and to reduce the weight and cost of the concentrator, second generation PRIDE designs utilise 6 mm wide solar cells at the absorber of dielectric concentrators. Injection moulding was used to manufacture 3 kW_p of PV concentrator modules with the PRIDE design suitable for building façade integration in Europe. PV concentrator modules achieved a power ratio of 2.01 when compared to a similar non-concentrating system. The solar to electrical conversion efficiency achieved for the PV panel was 10.2% when characterised outdoors. In large-scale manufacturing, a module cost reduction of over 40% is potentially achievable using this concentrator technology (Mallick and Eames, 2007). A prototype photovoltaic concentrator array called *Euclides* of 60.4 m^2 has been built using reflecting linear optics maintained in focus by horizontal single-axis tracking (Sala et al., 1996). The results from the *Ecluides* prototype showed a clear cost advantage with respect to flat modules. Efficiencies of 17% under 5× concentration have been achieved (Bruton et al., 2002).

7. Luminescent solar energy concentration for BIPV

7.1. Operating principle

For large-scale building façade BIPV applications low-cost non-tracking solar energy concentrators are required. The concentration restriction limits of non-tracking non-imaging optical systems, due to phase space conservation (Welford and Winston, 1979) do not apply to luminescent solar concentrators (LSC) (Goetzberger et al., 1985). A LSC illustrated in Fig. 15 consists of a transparent flat sheet of glass or plastic doped with fluorescent dyes for example Rhodamine 6G; Rhodamine B; Ruthenium byridyl and crystal violet. Light impinging on the surface of the concentrator is partly refracted into the fluorescent material and after absorption by the dye molecules; photons are re-emitted isotropically at a lower frequency (Zastrow et al., 1981; Goetzberger et al., 1985). The amount of photons depends on the absorptivity and on the fluorescence quantum yield (QY) – ratio of the number of photons fluorescing to the number of photons incident on the material. If the probability of emission is equal in all directions, part of the emitted photons will leave the medium and part will be reflected back at the surface of the medium. Since the refractive index of the layer is much higher than that of the external medium (air), a large proportion of the emitted photons will be trapped within the plate and transported by total internal reflection (TIR) to the edges. Reflectors are mounted on three of the edges and on the back surface, so light can only emerge along the fourth edge where it is absorbed by PV cells. These mirrors reflect light that may be incident on these surfaces outside the angular range for TIR. On their way to the edges, re-absorption (due to the overlap of the absorption and emission spectra) and light scattering (due to material and surface inhomogeneities) may take place. Absorption by the carrier material will also occur. A large Stokes shift, that is the ratio of the average energy of emitted photons to the average energy of the absorbed photons, will avoid self-absorption increasing the output of the concentrator (Markvart et al., 2005).

These concentrators in BIPV applications are the capability to (i) concentrate diffuse radiation as well as direct without tracking, by concentrating incident radiation from every direction, (ii) separate the solar spectrum into two or

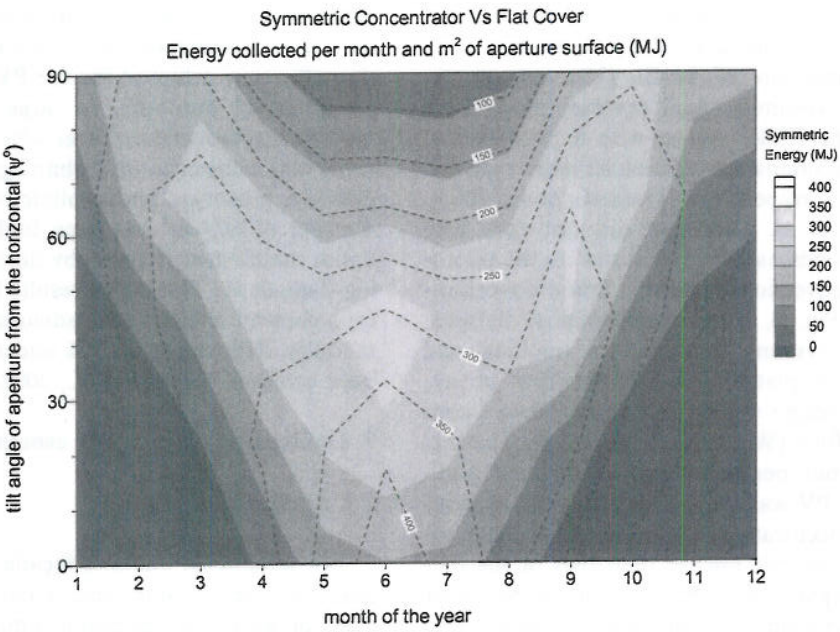

Fig. 14. Energy collected per month and m^2 of the aperture surface for the symmetric concentrating (flood) and the flat (dashed line) covers against the tilt angle ψ from the horizontal. The covers are located in London, UK (52°N) and facing south ($\gamma = 0°$ and $\beta = 0°$) (Zacharopoulos et al., 2000).

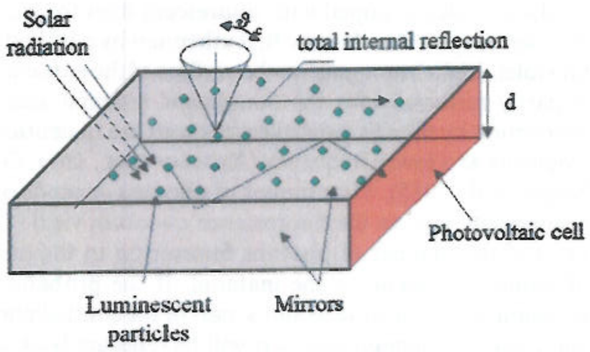

Fig. 15. A luminescent solar concentrator.

more parts, each of which may be converted to electricity with greater overall efficiency using different solar cells (Reisfeld and Jorgensen, 1982), (iii) when compared with geometric concentrators heat dissipation problems are reduced, and (iv) if the luminescent concentrator materials are of lower cost than the displaced PV, then the cost of BIPV electricity is lower.

The energy lost in shifting incident photons to longer wavelengths is distributed throughout the absorbing region of the converter as in the longer wavelength infrared radiation (Rapp and Boling, 1978). A LSC aims to shift the solar spectrum by fluorescence to a wavelength region where the specific solar cell response is higher (Goetzberger and Greubel, 1977; Rapp and Boling, 1978; Goetzberger and Wittwer, 1979). Panel efficiency is a function of dopant concentration and sheet thickness (Taleb, 2002).

7.2. Dye luminescent solar concentrator

Many fluorescing dyes have been synthesised with a great number available for textiles, advertising, scintillators or dye lasers, though the dyes used for fluorescent energy conversion require different properties. As many dye molecules have QYs close to 100% (e.g., Rhodamine 6G) and most of them operate in the UV and blue range of the spectrum, QY does not appear to be a serious barrier. Measurements have shown lower QYs for dyes fluorescing in the red and infrared regions where the silicon solar cells has its maximum sensitivity (Wood and Long, 1978; Kondepudi and Srinivasan, 1990), however, QY is improving (Jung et al., 2001). For an ideal LSC, the absorption and emission spectra should be well separated.

A stack of sheets doped with different dyes to match different luminescent wavelengths, demonstrated in Fig. 16a and b using LSCs as beam splitters can be coupled to PV cells with optimum sensitivities in different spectral ranges, (Goetzberger and Greubel, 1977). The main advantage of using a stack is that the concentrated light from individual collectors can then be transformed by correspondingly spectrally-optimised solar cells, with a higher overall efficiency (Reisfeld and Jorgensen, 1982) than can be expected with a single plate. The multi-stack device consists of several plates; the top plate absorbs the shortest wavelength radiation, which is then emitted as longer wavelength fluorescence. The consecutive total reflections transport this light to a PV cell with a relatively high-energy gap. The lower plates absorb at increasing wavelengths and their luminescent species emit further down in the red or infrared (Wittwer et al., 1984). An advantage of multi-stack LSC is that approximately half

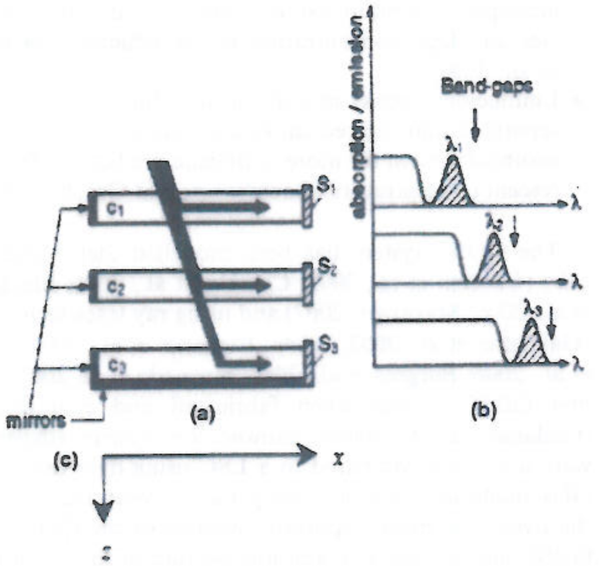

Fig. 16. A schematic of a stack of three collectors (c1–c3) with three solar cells (s1–s3) in series (a). The absorption and emission spectra of the molecules in the collectors (b) (Goetzberger, 1978).

of the radiation emitted within the critical cone can be recovered by the next plate below as in Fig. 16b. A narrow air gap between the upper plate and the second plate is necessary to prevent luminescence in the upper plate penetrating into the lower plate and becoming absorbed. It is impracticable to make stacks of more than three plates (Reisfeld and Jorgensen, 1982) and that it is probable that two plates is often optimal. In a multilayered structure the physical separation of chemically active species improves dye stability and better control over dye concentration, higher optical density can be obtained by building up multiple layers of the same dye (Hermann, 1982).

A thin film fluorescent concentrator consists of a film of ~1 mm thickness deposited on an undoped optically transparent substrate several millimetres thick (Friedman, 1981) in which absorption and emission by the dye occur in the thin film rather than throughout the glass or plastic substrate. The advantage of thin films having optical contact with a transparent thicker plate is that the fluorescence emitted from the dyes in the thin film is trapped in the entire film-substrate composite and thus the parasitic losses due to self-absorption and scattering from impurities can be reduced greatly compared to bulk doped plates (Reisfeld et al., 1988). In order for trapping to be efficient in the composite (as opposed to trapping in the thin film alone), the refractive index of the film should be either slightly less than or the same as that of the substrate, (Grande et al., 1983). The thin film approach allows a dye-doped film to be deposited on glass as well as plastic substrates. Because of the higher dye concentrations in the thin film, efficient energy transfer might also be achieved between co-doped dyes. Finally, if a glass substrate is used, it can also be doped with inorganic ions, thereby, shielding the dyes from UV radiation while at the same time pumping them fluorescently (Friedman, 1981). A glass-plastic hybrid system may be made by combining dyes which absorb in the visible spectral region with luminescent glasses absorbing in the UV and IR region of the spectrum.

For a solar energy conversion, high UV chemical stability is required, but under UV irradiation dyes decompose (Mansour, 1997, 1998; Mansour et al., 1998 and Salem et al., 2000). In solar collector applications this may be prevented by using a filter to exclude UV wavelengths. After 200–400 h of continuous exposure to radiation, a reduction of 15–20% was observed in the optical density and intensity of the luminescence of polymer plates with Rhodamine 6G, Coumarin and other luminophors (Batchelder and Zewail, 1979; Wittwer et al., 1984). Overlap of absorption and emission spectrums competes with the escape of the fluorescence and lowers the QY. Even when absorption and fluorescence bands are separated in liquid solutions, they exhibit a large overlap in a rigid medium such as films containing dyes. The effect of self-absorption may be reduced by adding polar molecules of high mobility to the dye before forming the thin film (Taleb, 2002). Such mixing allows for better separation between absorption and fluorescence bands and hence increases the LSC efficiency.

7.3. Quantum dot solar concentrator

Quantum dots (QD) (Reed, 1993) are man-made nanostructures that typically vary from tens to hundreds of nanometers in size (Gerion et al., 2001). These dimensions are of the order of the electron de Broglie wavelength and so electrons confined in these low dimensional semiconductor structures exhibit electronic and optical characteristics similar to those in atoms (Akkermans et al., 1995; Weinmann, 1997; Banyai and Koch, 1993). Due to these quantum size effects, both the absorption spectrum and the emission spectrum of semiconductors shift to higher energies with decreasing particle size away from the red end of the spectrum, as the crystallite becomes smaller; Fig. 17 illustrates the spectral shift with size, for cadmium selenium (CdSe) QDs, (Sattler, 2002). The occurrence of such a redshift in the emission spectrum relative to the absorption spectrum is seen in QDs of Si, CdSe, InP and InGaAs and exists irrespective of the preparation methods of the dots (Fu and Zunger, 1996). The redshift arises from the size distribution in dot samples: the larger dots in a sample have lower band-edge energies so if the sample is excited with sufficiently high-energy photons above the band edge of the smallest dot, the emission will be redshifted because it results from the deexcitation of band edges of all the dots in the sample (Fu and Zunger, 1996). QDs are capable of absorbing light over an extremely broad wavelength range as illustrated in Fig. 18 which depicts the absorption spectra of InP QDs. The absorption spectra illustrates the spectral shift to higher energy as QD size decreases (Micic et al., 1998).

In a Quantum Dot Solar Concentrator (QDSC) the fluorescent dyes are replaced by quantum dots (QDs). Insola-

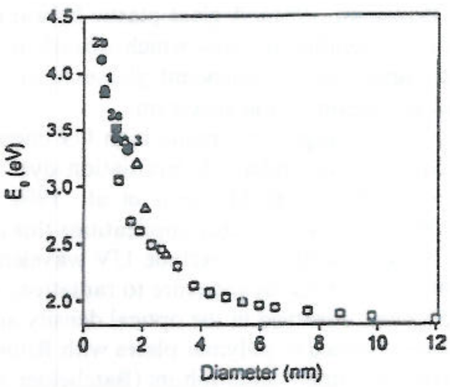

Fig. 17. Size dependence of bandgap of CdSe particles (Sattler, 2002).

tion absorption by a QD leads to the emission of lower frequency photons; the number that is emitted depends on the carrier material absorptivity and the QD quantum efficiency. As in an LSC with dyes, emitted photons may leave the carrier material or be reflected at the device surface to remain within the concentrator. If the refractive index of the carrier material is higher than that of the surrounding medium (in this context, air), a large proportion of the emitted photons will reach the edges by total internal reflection. The asserted advantages of QDs over dyes are:

- QDs are nanometer sized crystalline semiconductors and degrade less than organic dyes.
- High fluorescence QY has been observed in QDs at room temperature (Blanton et al., 1996; Alivisatos, 1998).
- The absorption threshold can be tuned by choice of dot diameter. Colloidal InP QDs have thresholds which span the optical spectrum (Micic et al., 1997).
- Red shift between absorption and luminescence is determined primarily by the spread of dot sizes, which in turn can be optimised by choice of growth conditions. Re-

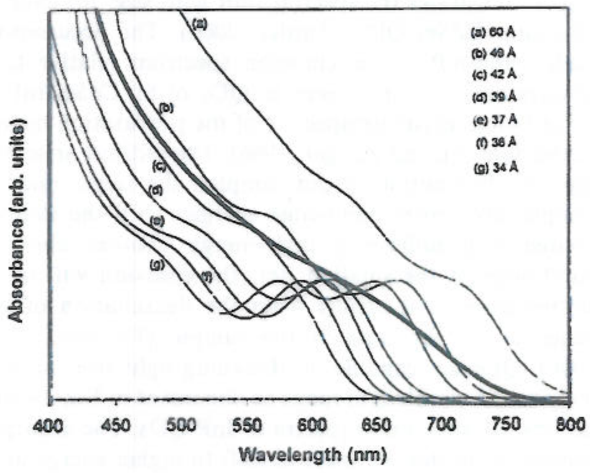

Fig. 18. Absorption spectra of InP QDs after the initial colloidal preparation (bold line) and after size selective precipitation (spectra for QD sizes of 26–60 Å) (Micic et al., 1998).

absorption therefore can be minimised and high efficiencies and high concentration ratios achieved (Barnham et al., 2000).

- Luminescent peaks and absorption thresholds are well separated and the red shifts are comparable with those assumed even in the more optimistic predictions for fluorescent concentrators (Goetzberger and Greubel, 1977).

The QDSC system has been modelled thermodynamically (Chatten et al., 2003; Chatten et al., 2006; Markvart et al., 2006; Markvart, 2007) and using ray trace techniques (Gallagher et al., 2002, 2004a; Richards et al., 2004; Slooff et al., 2006; Burgers et al., 2006; Kennedy et al. 2007). The first QDSC system when fabricated and characterised (Gallagher et al., 2004b) showed low system efficiencies were low when compared to a LSC using dyes due to the QDs quantum efficiency being much lower than that of the dyes. The most important features of the QD for the QDSC are the high QY and low overlap of the absorption and emission bands. If QDs with >0.99 QE can be incorporated into a suitable transparent media then QDSCs which perform in the upper range of efficiency predicted for dye concentrators may be realised, (Gallagher et al., 2007a,b).

Building from previous work on the LSC and replacing dyes with QDs a range of designs have been studied, in flat-plate design (Barnham et al., 2000; Chatten et al., 2003; Gallagher et al., 2002; Gallagher et al., 2004a,b; Gallagher et al., 2007a,b; Barnham et al., 2006; Rowan et al., 2006; Reda, 2008) stacked plates (Farrell et al., 2006) different geometries (Rowan et al., 2007; Kennedy et al., 2007) and thin films (Schüler et al., 2007). The use of photonic layers (Goldschmidt et al., 2006) to trap the absorbed incident radiation and the use of passive luminescence layers (van Sark et al., 2004; van Sark, 2006) for up-conversion (Richards, 2006) and down-conversion (Shalav et al., 2007) have been investigated. In each case a layer above the solar cell is designed to absorb photons outside the cell bandgap and emit within the cell bandgap. This requires a broad-band absorption from the dye or QD and 100% efficiency (or transparency) in spectral regions close to the band edge. Mixing dyes and using different size distributions of QDs could broaden absorption QDs embedded in dielectric layers directly above traditional devices might readily add 3–5% to device efficiency with little extra cost (van Sark, 2006). Commercially-available QDs do not presently have a high enough QY to enable a highly efficient device to be fabricated (Gallagher et al., 2004a,b, 2007a,b; Sholin et al., 2007, however, NIR QDs do show promise for this application (Kennedy et al., 2009)).

8. Thermal management of BIPV

8.1. Thermal effects on BIPV conversion efficiency

Only a part of the solar energy spectrum absorbed by a PV material is converted into electrical energy, the rest is converted into heat, resulting in increased solar cell temperature. Module temperature is a function of ambient temperature, the thermal properties of module encapsulation materials and the thermal effects of the mounting structure. When the cell temperature increases, the band gap in the junction is reduced and therefore more photons are able to participate in electron–hole pairing causing reduction of the direct band gap (Fahmy, 1998) thereby diminishing electricity production. The photocurrent though increasing slightly with increasing operating temperature due to band gap shrinkage (and associated expansion of the photoresponse spectrum to longer wavelengths) will not be sufficient to compensate for the drop in the open circuit voltage V_{oc} and fill factor (FF) of the I–V characteristic due to the saturation current rising exponentially with temperature (Andreev et al., 1997). Increasing temperature therefore reduces the available potential difference across the junctions to drive the desired forward current. The relationship between temperature and efficiency varies with cell material. For a crystalline silicon module, the power output decreases by approximately 0.4% K^{-1}, whereas for a-Si this value is approximately −0.1% K^{-1} (Bücher, 1997). In crystalline silicon solar cells for each 1 K rise in cell temperature, the open circuit voltage decreases by ≈2 mV and cell output power decreases by 0.4–0.5%, respectively, from a base of 25 °C (Fahmy, 1998; Krauter et al., 1994; Batagiannis and Gibbons, 2001). The temperature effect on cell operation is shown in Fig. 19 (Markvart, 1994). PV current output is relatively stable at higher temperatures, however, the voltage is reduced, leading to a reduction of solar to electrical conversion efficiency as the cell temperature is increased (Ingersoll, 1986; Cross et al., 1994). The thermal properties of PV elements are reported in terms of thermal resistance (Fuentes and Roaf, 1997). The temperature of the PV element can be calculated by (Watt et al., 1998a,b, 1999).

$$T = (1 - \eta)I\,R$$

where the thermal resistance R has measured values shown in Table 3. Protecting electronic modules from excessive temperatures may be accomplished by: (i) active cooling systems, such as air-conditioning, requiring AC power and high levels of maintenance; (ii) assisted systems, such as air-to-air heat exchangers, which use DC power, but require less maintenance than the active system; (iii) maintenance free passive systems requiring no power (Prudhoe and Doukas, 1990; Ghiraldi, 1988) and/or (iv) removing and storing the excess heat from the PV cells using phase change material (PCM) (Huang et al., 2004, 2006a,b, 2007; Hasan et al.,2007a,b).

8.2. BIPV thermal management using phase change materials

A material undergoing a phase change absorbs or releases latent heat at a relatively constant temperature, PCMs can be used in thermal management schemes where heat input/dissipation is periodic, or is a sudden transient

Table 3
Thermal resistance of different building integrated PV element.

		Type of BIPV system	Reference
Thermal resistance R ($KW^{-1} m^2$)	0.031	Roof integrated	Schmid (1992)
	0.022	Free standing module	Schmid (1992)
	0.052	Roof integrated modules	DeGheselle (1997)
	0.032	Vertical rainscreen cladding	Wilshaw et al. (1995)
	0.035	Northumberland ventilated façade	Wilshaw et al. (1997)
	0.042	Façade	Nordman et al. (1997)
	0.024	Roof	Nordman et al. (1997)
	0.042	Flue ventilated shingles	Okuda et al. (1994)
	0.05	Closed flue	Okuda et al. (1994)
	0.041	Ventilated roof integrated	Laukamp et al. (1995)
	0.066	Non-ventilated façade integrated modules	Laukamp et al. (1995)

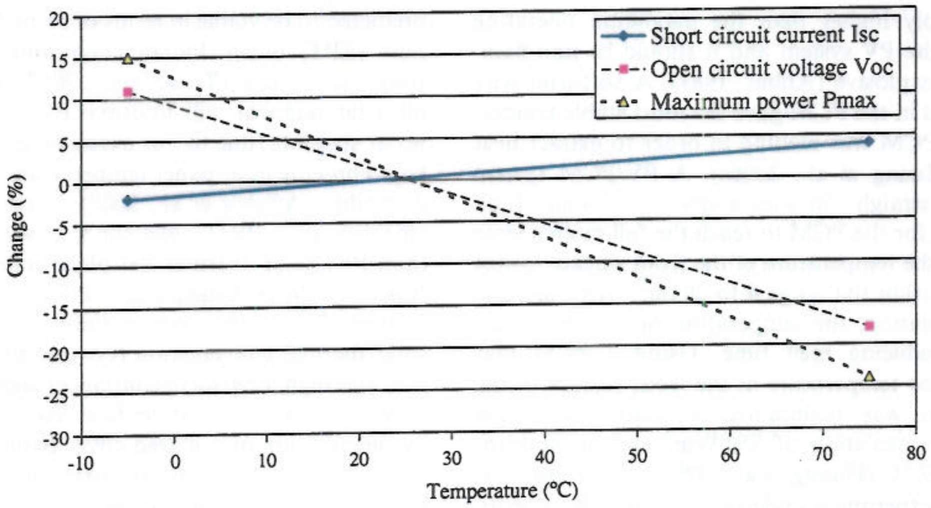

Fig. 19. The effect of temperature on cell operation (Markvart, 1994).

(Salyer and Sircary, 1990, 1997). The absorption of large amounts of energy at a constant temperature is one of the main attractions of PCM for temperature control. Use of aluminium foam can increase effective PCM thermal conductivity with the choice of suitable foam being a function of the heat load, PCM module geometry and thermal boundary conditions (Pal and Joshi, 1997, 1999). Currently available solid–liquid PCMs can be conveniently classified into three major categories (Jotshi et al., 1991, 1992; Antohe et al., 1996): inorganic compounds (Kimura and Kai, 1988), organic compounds, and eutectics of inorganic and/or organic compounds (Feldman et al., 1989). For the BIPV thermal control, organic-based PCMs in particular those which are paraffin-based, have the advantages of high heats of fusion, negligible supercooling, and low vapour pressure in the melt, are inert chemically, stable and self nucleating, have no phase segregation, are non-toxic and noncorrosive, inexpensive and widely available (Leoni and Amon 1997). Significant disadvantages of paraffin wax are low thermal conductivity (about one-half that of salt hydrates), large volume change during melting and freezing (approximately 10% by volume expansion or contraction) leading to leakage in the liquid phase, high wetting ability and flammability. Elastic containers and different container geometries may be used to overcome the volume change on melting and freezing.

A system using a phase change material (PCM) to moderate the BIPV temperature rise (PV/PCM) has been designed, fabricated, tested and simulated (Huang et al., 2004). Small scale practical experimental tests were carried out both in the laboratory and outdoors (Huang et al., 2006a; Hasan et al., 2007a,b). Three different PV/PCM systems were subsequently modelled, to determine the effect on BIPV temperature evolution of form of cooling fins for two different types of phase change materials. While the conventional aluminium fined PV panel with natural ventilation can reduce the temperature rise of the PV, the use of a PV/PCM system can reduce the temperature rise of the PV much further. The PCM should have a flash point considerably higher than the maximum operating temperature of the PV system and it should be non-flammable and non-explosive (Abhat, 1981). A soft-iron wire matrix embedded in the PCM gave the most stable temperature when the PCM was melting in order to extract heat from the PV (Huang et al., 2006a). A PV/PCM system incorporating a straight fin with a spacing of 4 mm took the shortest time for the PCM to reach the full molten state and maintained the temperature of the front surface lowest for fin spacing within the range 4 to 20 mm. With increasing incident insolation, the temperature on the front surface increases reducing melt time. Using a PCM that melts at 25 °C, the temperature at the front surface of the PV/PCM system was maintained at below 29 °C for 130 min with an insolation of 750 Wm^2 and an ambient temperature of 23 °C (Huang et al., 2006a). In an outdoor characterisation experiment undertaken in the UK, a depth of 40 mm of a paraffin-waxed based PCM with a melt point of 25 °C was shown to provide significant PV temperature control and thus increased electrical conversion efficiency. Granular PCM that melts at 40 °C can be used to reduce the temperature rise of a BIPV panel, however, the thermal control is not as effective as when using solid–liquid 25 °C melt PCM (Huang et al., 2006a).

A three-dimensional (3D) numerical model has been developed to simulate the use of a phase change material linked to a PV system to control the temperature rise of BIPV. The model was used to predict temperatures, velocity fields and vortex formation within the system (Huang et al., 2006b). The 3D model was compared successfully with a 2D finite-volume heat transfer model (Huang et al., 2004) and validated experimentally. Velocity and temperature fields inside a PV/PCM system could be predicted successfully for a range of system geometries. Altering the boundary conditions employed in the simulations of the PV/PCM system allowed for different levels of insolation, ambient temperatures and convective and radiative heat transfer to the surrounding environment. For simple line-axis systems the 2D model simulated accurately the predictions made using the 3D model. The temperature distribution within the PCM obtained using five pin fins to improve the heat transfer into the PCM has also been reported (Huang et al., 2007). Temperature distributions predicted for different insolation and ambient temperatures at the photovoltaic surface show that the lower temperature achieved leads to significant improvement in the operational efficiency of photovoltaic facades.

8.3. Water and air-heating BIPV

Where BIPV heat removal uses water (or an aqueous propylene glycol solution) as the working fluid, the cost is much higher due to the required plumbing, more complex façade and building hydronic systems integration and greater weight. Careful system output optimisation of water-heating "PV/T" systems is thus required to justify the initial capital cost investment though they have been predicted to be viable in terms of embodied energy payback time (EPT) under Indian conditions with EPT ranging from 4 to 14 years (Tiwari et al., 2007). Whilst BIPV hydronic heat removal will improve PV efficiency, should the water stagnate (due to, for example, pump failure) the very high consequential panel temperatures adversely affect PV durability (Affolter et al., 2000). Furthermore the thermal efficiency of a PV/T collector is lower than an optimised (non-PV) solar thermal flat-plate collector (Sandnes and Rekstad, 2002; Almeida and Olivera, 2008) due usually to most PV having poor radiative surface properties for solar thermal conversation (i.e. low solar thermal absorption and high long-wave emittance) and lack of an aperture cover to inhibit convective heat loss. Rectifying the latter by the addition of a glazed cover reduces PV performance due to increase PV optical losses and raises PV temperature. Despite these design challenges in appropriate conditions they can be viable economically. For example in

Portugal payback times of between four and six years have been estimated for domestic installations (Almeida and Olivera, 2008). There are now over 25 types of water-heating PV/T systems have been available (Fraisse and Souyri, 2003) and their development continues (Fraisse et al., 2007; Charalambous et al., 2006).

Flat-plate air-heating photovoltaic solar thermal collectors also seek to yield an optimal combination of both electrical and thermal conversion efficiencies. Both steady–state (Cox and Raghuraman, 1985; Garg et al., 1991; Bhargava et al., 1991) and transient (Aste et al., 2008) energy and exergy (Joshi and Tiwari, 2007) analyses of such collectors have been developed. System length, mass flow rate, duct depth and packing factor were analysed by Bhargava et al. (1991) to compute the optimum photovoltaic cell area necessary to generate electricity sufficient to power the system's fan. A composite Trombe-Michel wall illustrated in Fig. 20 was modelled for a PV panel integrated into building facade (Zrikem and Bilgen, 1987; Mootz and Bezian, 1996). Air is drawn in through the inlet section, heated by solar radiation in the convection channel and discharged through the outlet section. Additional heat is delivered to the adjoining room by conduction through the solar PV panel and the insulation. The best electrical PV panel performance during convective heat recovery periods occured at the maximum channel spacing (Mootz and Bezian, 1996). Variable channel spacing proved to be the most efficient solution for both convective heat recovery and non-recovery periods.

A BIPV façade can act as an unglazed thermosyphon photovoltaic-thermal air-heating collector to provide natural ventilation in summer (Wang et al., 2006), pre-heated air in winter and electrical output throughout the year (Humm and Toggweiler, 1993; Sick and Erge, 1996; Bazilian and Prasad, 2002; Posnansky et al., 1992; Posnansky and Eckmanns, 1995; Lloret et al., 1995; Bloem and Ossenbrink, 1995, 1996; Wouters et al., 1996; Bendel et al., 1995; Shaw et al., 1995). A duct arranged behind the PV module

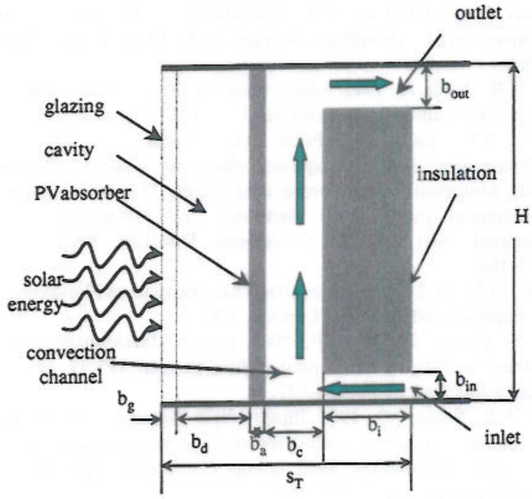

Fig. 20. Model for PV panel integrated into a building facade (Mootz and Bezian, 1996).

or mounting system, allows air flow induced by buoyancy from the back of the PV panel in a similar manner to a thermosyphoning air panel (Norton et al., 1992). The movement of the air in this duct is governed by a combination of natural convection (stack effects), and wind induced flow (Batagiannis and Gibbons, 2001). The temperature attained depends on the incident solar energy, surface area surrounding ambient air temperature, flow conditions, radiant surfaces, and cooling mechanisms and the flow and temperature distribution (Mosfegh et al., 1995; Yang et al., 1996; Sandberg and Mosfegh, 1996; Mosfegh and Sandberg, 1998; Brinkworth et al., 1997; Tonui and Tripanagnostopoulos, 2008). For air flow in a PV rear duct section, one wind direction may aid the air movement, and induce greater cooling of the modules, another wind direction may act against the required airflow direction, and reduce the cooling potential (Batagiannis and Gibbons, 2001). For a naturally-ventilated PV cladding element, buoyancy forces are balanced by the pressure drops due to the friction at the entrance and exit (Brinkworth et al., 2000). For zero wind velocity, flow through a PV ventilated stack is driven by buoyancy forces alone. In other cases the flow inside the duct becomes a mix of free and forced convection. In a long shallow duct flow is determined by internal flow resistance and the flow structure can be characterised by entrance lengths and the transition to turbulence. For a single vertical loop it was reported that the mass flow rate increased by 1.9 ms^{-1} when the heat input to the duct increased from 50 to 300 W (Brinkworth, 2000). Buoyancy induced airflow in a duct between the BIPV and the wall, even with a low mean airflow velocity of 0.1 ms^{-1}, has been shown to reduce BIPV operating temperature by between 15–20 °C giving a 15% increase in electrical conversion efficiency (Brinkworth et al., 1997).

Heat transfer within the cavity of a single concentrator, multiple concentrators, the space between adjacent concentrators and in an air duct behind the photovoltaics has been analysed for the low concentrating photovoltaic applications. Heat transfer in an asymmetric compound parabolic photovoltaic concentrator suitable for building façade integration has been investigated (Mallick et al., 2007). Free and forced convection at the rear of a PV concentrator provided a significant PV temperature reduction. A maximum possible solar cell temperature of 95 °C was predicted for an incident insolation of 1000 Wm^{-2}, this decreased solar cell efficiency by 25% compared to a PV panel operating at the STC (Mallick et al., 2007). An inlet air velocity of 1.0 ms^{-1} in a 20 mm wide channel between the aperture cover and the reflector, decreased the PV cell temperature by 25.4 K. A further reduction of temperature was achieved by providing an air channel to the rear of the aluminium back plate. The predicted air velocity in the space formed between the reflector troughs was very small, due to the enclosed nature of the boundary and near uniform boundary temperatures. A maximum temperature reduction of 34.2 K was predicted for a front and rear air gap of 20 mm with an inlet air velocity of 1.0 ms^{-1} (Mallick et al., 2007).

The individual frames of each BIPV module can intrude into the air flow path. In order to reduce internal pressure drops in the cavity, the rear of the BIPV needs to be smooth, and the cross-section of the duct large. However, a smooth surface minimises the area for heat transfer, and a large cross-section reduces the air velocity over the surface. Both laboratory measurements and modelling have suggested that a duct depth of 100 mm is a reasonable optimum for the required airflow rates and velocities (Batagiannis and Gibbons, 2001). Without either regularly replaced or cleaned filters, airborne dust accumulation on a duct surface can also reduce the rate of heat transfer from the BIPV (Goossens and Kerschaever, 1999; Bilgen, 2000), Extended fins have be introduced into the flow to increase surface area, however, these also increase rear duct pressure losses, and their weight adds to the structural load placed on the building (Batagiannis and Gibbons, 2001).

9. Conclusion

The cost of a BIPV system can be lowered by reducing PV module and component manufacturing costs, installation costs, operation and maintenance costs and improving PV and other component efficiencies. Considerable enhancement of BIPV system performance is, however, achievable without improvement in PV cell performance. Given that the latter has, and will, continue to improve, the prospects for a greater range of viable BIPV applications is promising. The drivers can sometimes seem perverse, for example, the recent temporary shortage of silicon feedstock has led to advanced production technologies, thin film modules and concentrator devices being introduced more rapidly to the market (Jäger-Waldau, 2006) and more competition between manufacturers of BIPV specific systems (rather than PV modules). Cost and efficiency remain barriers to the widespread use of BIPV. Government subsidies and tax reduction on different BIPV products have been necessary to stimulate market development (Maycock, 1997). Many countries have such enhanced market stimulation mechanisms that should aid the achievement of economies of scale. Incorporating PV materials into products such as roofing materials, windows and awnings provides the opportunity for cost reduction by replacing common building materials with PV materials at marginal costs. In the future we can envisage, for example, LSCs comprise QDs or dyes seeded in plastic or glasses building façadès with photovoltaic (PV) cells attached to the edges, converting the direct and diffuse solar radiation into electricity for use in the building. Operation and maintenance costs can be reduced by using better more reliable fault tolerance systems and equipment. There factors will render BIPV more viable economically in a greater range of locations.

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